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CK-153975

THE APPLICATION OF LANDSAT DATA TO DELIMITATION OF AVALANCHE HAZARDS  
IN MONTANE COLORADO: FINAL REPORT

NASA Contract NAS5-20914

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June 1977

Type III Report for the Period 28 February 1975 - 28 April 1977

Prepared for  
National Aeronautics and Space Administration  
GODDARD SPACE FLIGHT CENTER  
Greenbelt, Maryland 20771



(E77-10211) APPLICATION OF LANDSAT DATA TO  
DELIMITATION OF AVALANCHE HAZARDS IN MONTANE  
COLORADO Final Report, 28 Feb. 1975 - 28  
Apr. 1977 (Colorado Univ.) 122 p  
HC AC6/MF A01

N77-31565

Unclas  
CSCL 08L G3/43 00211

## TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle Application of LANDSAT Data to Delimitation of Avalanche Hazards in Montane Colorado: Final Report		5. Report Date	
		6. Performing Organization Code	
7. Author(s) Compiled and Edited by Daniel H. Knepper, Jr.		8. Performing Organization Report No.	
9. Performing Organization Name and Address. Institute of Arctic and Alpine Research University of Colorado Boulder, Colorado 80309		10. Work Unit No.	
		11. Contract or Grant No. NAS5-20914	
12. Sponsoring Agency Name and Address James Broderick LANDSAT Technical Monitor, Code 902 NASA/Goddard Space Flight Center Greenbelt, MD 20771		13. Type of Report and Period Covered Type III 2/28/75 to 4/28/77	
		14. Sponsoring Agency Code	
15. Supplementary Notes			
16. Abstract LANDSAT imagery of the Colorado mountains has been employed to prepare 1:250,000-scale snow avalanche hazard maps of the Leadville, Montrose, and Durango quadrangles. Imagery analysis has shown that direct indicators of past avalanche activity are generally not recognizable because of resolution and the lack of unique spectral properties for avalanche hazard zones. However, general knowledge of avalanche characteristics for the region, specifically, the elevation above which sufficient snowfall is probable and the minimum slope steepness necessary for avalanches to start, can be used to eliminate the unavoidable errors of omission that occur with imagery analysis alone. Three levels of avalanche hazard were mapped using LANDSAT imagery and supplemental data. In order of increasing reliability, they are: (1) potential avalanche zones--areas above 9,000 feet and steeper than 22 degrees defined from topographic maps; (2) interpreted avalanche zones--interpreted from LANDSAT imagery; (3) active avalanche zones--compiled from existing detailed avalanche hazard maps. The resultant maps are reasonably accurate and consistent, although they cannot substitute for detailed avalanche hazard investigations. Characteristic terrain patterns can be recognized over some areas of known landsliding, however, many landslide areas cannot be detected.			
17. Key Words (Selected by Author(s)) snow avalanche regional mapping landslides LANDSAT		18. Distribution Statement	
19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*

## PREFACE

Over the last several years, the Institute of Arctic and Alpine Research (INSTAAR) at the University of Colorado has been involved in the delineation, mapping, and analysis of natural hazards in selected portions of the Colorado Rocky Mountains. Much of this research has been concerned with the detailed delineation of snow avalanche hazards using air photo and field mapping techniques. Continuous monitoring of various environmental parameters during the winter avalanche cycle has produced significant advances in the field of avalanche prediction and forecasting for local areas.

In June 1975, INSTAAR began research for the National Aeronautics and Space Administration (NASA contract NAS5-20914) on a new approach to avalanche hazard investigation. The objective of this research was to analyze, evaluate, and apply LANDSAT imagery for delineating and mapping avalanche hazards in the Colorado mountains. Secondary, and purely experimental, objectives of the research were to examine the potential of LANDSAT - derived information as input to avalanche forecast or warning systems and to evaluate the usefulness of LANDSAT imagery for mapping major landslide areas.

Early in the study, an attempt was made to compile historical avalanche records in order to more completely define known avalanche paths and obtain some information on the recurrence interval of known paths. It was found that there is very little readily accessible historical data. Most accounts of avalanching are contained in old newspapers, although the much information can be derived from long-time residents in the mountain communities. From the initial attempt to compile these data for the general area of Hinsdale County, Colorado, it became quite apparent that this work could require

many years to complete for the entire Colorado mountain region. Furthermore, these data are highly selective because only those avalanches that cause death or destruction are reported. Consequently, this aspect of the study was abandoned.

LANDSAT images of the San Juan Mountain area of Colorado were examined to determine what avalanche and avalanche-related features could be detected and the degree to which identification can be made. The only feature produced by avalanches that was found is trimlines. No evidence of actual snow movement was found in the sidelap area of any of the consecutive-day images studied. However, even trimlines could not be consistently identified because other natural and artificial processes can create identical vegetation patterns.

Regional avalanche hazard mapping, then, must rely on interpreting indirect indicators of avalanche zones. The most important factors are elevation (climatic zones of high snowfall) and topography (slope steepness and profile). LANDSAT imagery alone, however, is not sufficient for identifying these features, mainly because of the lack of elevation data and topographic data due to incomplete stereoscopic coverage. Both of these factors and the critical vegetation patterns on the imagery can be evaluated simultaneously by using a topographic map printed on a transparent base over the image during interpretation; interpreted avalanche hazard zones can be plotted directly on the map. Testing of this mapping technique revealed that those areas interpreted as avalanche hazard zones are nearly always actual avalanche zones, but a significant number of actual avalanche zones escape interpretation. Consequently, regional avalanche hazard maps prepared from LANDSAT imagery and a topographic overlay were judged too inconsistent and unreliable to be useful.

To produce a more reliable and complete regional avalanche hazard map, it was necessary to draw on readily-available supplementary information, as well as detailed information and experience in known avalanche areas. A three-level avalanche hazard classification representing increasing degrees of accuracy, consistency, and probability of recurrent avalanching was applied to snow avalanche hazard mapping in the Leadville, Montrose, and Durango 1:250,000 quadrangles. The lowest hazard class is potential avalanche zones. These are defined as areas above 9,000 feet elevation that slope greater than 22 degrees and were determined by analysis of the 1:250,000 topographic maps. The intermediate hazard class is avalanche zones interpreted from LANDSAT imagery. The highest hazard class is active avalanche zones compiled from available detailed avalanche hazard maps.

Current methods of avalanche forecasting rely on meteorological and snowpack data collected within known avalanche zones and are limited to the immediate area in which the measurements are made. Avalanche predictions are generally moderately reliable within a 24-hour period; there are no long range regional avalanche forecasts except for general warnings issued by the U.S. Forest Service. Because of the time delay involved in acquiring imagery and the relatively low level of the state-of-the-art in avalanche forecasting, information from LANDSAT imagery does not appear to be useful at the present time.

LANDSAT imagery was examined to determine its potential usefulness for identifying and mapping major landslide areas in Colorado. Terrain patterns produced by landsliding can be recognized in selected areas, but other well-known landslide areas cannot be detected. Consequently, use of LANDSAT imagery is not recommended for areas where aircraft imagery or photography is available.

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APPLICATION OF LANDSAT DATA TO  
DELIMITATION OF SNOW AVALANCHE HAZARDS

AVALANCHE HAZARD CHARACTERISTICS

Snow avalanches, spectacular and often violent agents of erosion and deposition, occur when a volume of snow breaks loose from the more stable snowpack and slides or flows down a slope under the influence of gravity. The evolution of an unstable snowpack, and the trigger that sets the snowpack in motion, are influenced by a variety of factors, most importantly, in-coming solar radiation, temperature, snowfall, and wind conditions. It is the history of these factors over a period of hours to weeks, as well as conditions at the time of release, that govern the type and magnitude of an avalanche event, and these factors are often quite variable even over relatively small areas. Consequently, prediction of avalanche activity must be based on continuous monitoring of snowpack and meteorological conditions at stations located within the avalanche hazard zones, as well as a record of historical observations (usually lacking in the Colorado Rocky Mountains). Generally, the predictions are applicable only to the avalanche hazard zone in which the field data are collected, but some predictions for nearby areas are possible at reduced levels of success.(1).

We can, however, identify and map avalanche hazard zones, so that precautions can be taken to reduce or eliminate the effects of possible avalanche activity (2). Avalanche hazard mapping depends on the ability to recognize effects of past avalanching on the terrain and to identify terrain that is conducive to avalanching, even though physical evidence of past avalanche activity is lacking. To attain the capability, it is first necessary to understand the anatomy of an avalanche path and the various types of avalanches that occur in nature.

## AVALANCHE TERMINOLOGY

An avalanche path consists of three basic parts: starting zone, track, and runout zone (Fig. 1). The starting zone is where the initial mass failure of the snowpack occurs. Once movement has begun, additional snow becomes incorporated as the avalanche travels downslope, but it is usually the size of the initial mass failure that ultimately determines the magnitude of an avalanche event. Starting zones range from small "points" of 2 hectares or less to entire catchment basins as large as 40 hectares. Generally, the large catchment basin areas (mostly above timberline) do not entirely release during a single avalanche event, and the resulting avalanches are smaller than the maximum possible event. However, it is the area covered by the larger, though infrequent, events that defines snow avalanche hazard zones. A variety of terrain factors control where avalanches may begin, but the angle of slope and the terrain roughness are the most important. Most avalanches start on slopes between 30 and 45 degrees. Slopes steeper than 45 degrees are usually kept free of snow by constant sloughing, and slopes gentler than 30 degrees are insufficient for initiating snow movement except during extremely unstable conditions resulting from heavy snowfall, rapid changes in temperature, excessive melt water or rain, or extreme wind loading (3).

The major portion of the downslope movement of avalanching snow occurs in the avalanche track. Avalanche tracks vary widely in size and shape, and are of considerable importance in estimating the degree of avalanche hazard in a given area. Many large avalanche paths are characterized by tracks contained within a linear or curvilinear

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Figure 1a. Enlargement of a color infrared aerial photograph showing confined avalanche paths along U.S. Highway 550 between Ouray and Silverton, Colorado (NASA Mission 213, roll 59, frame 0129). Note bowl-shaped starting zones, tracks marked by well-defined trimlines, and deforested runout zones. Point A is common to Figures 1a, 1b, and 1c.



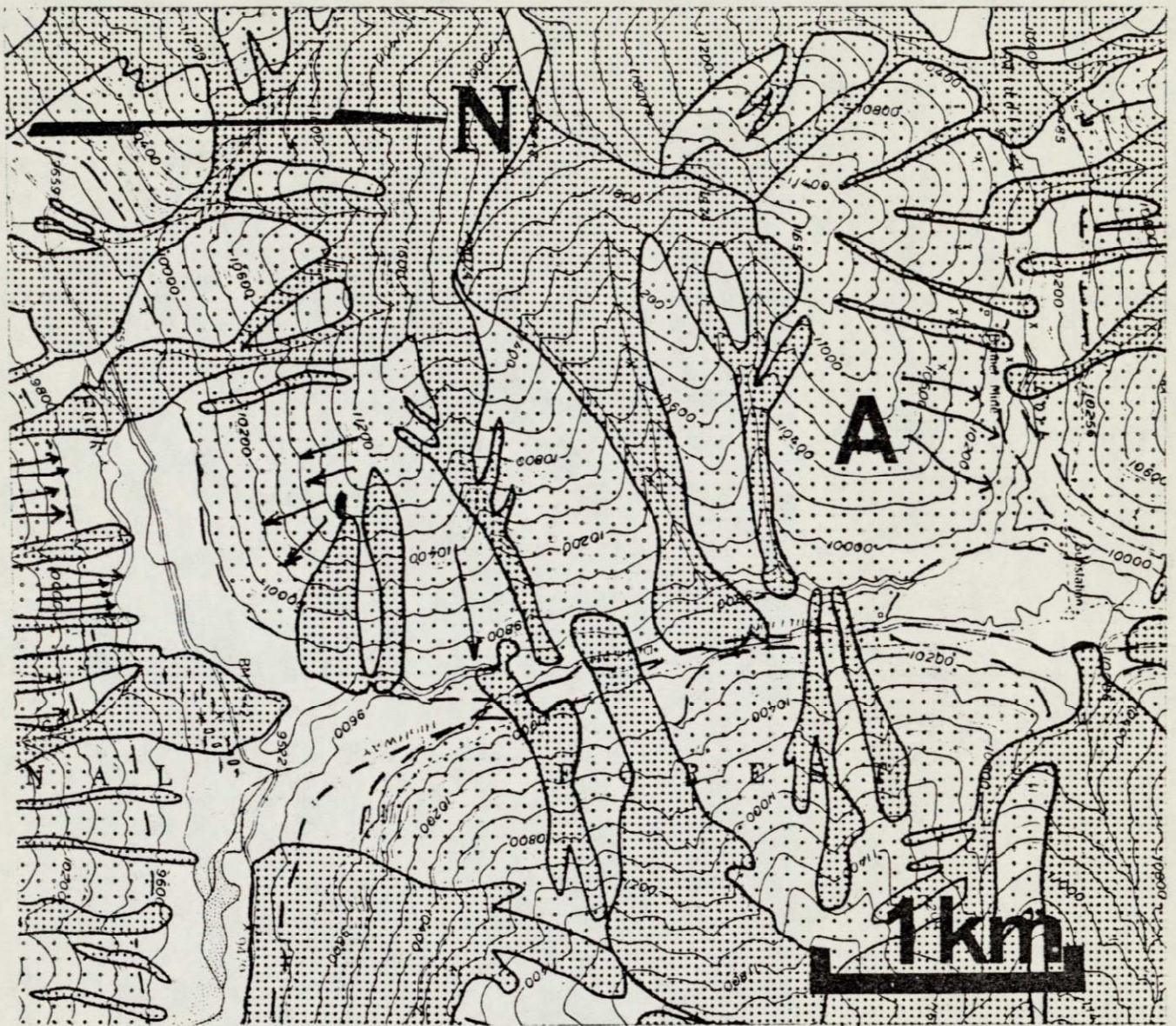


Figure 1b. Detailed avalanche hazard map of a portion of the Silverton 7.5-minute quadrangle (1:24,000), San Juan Mountains, Colorado (9). Point A is common to Figures 1a, 1b, and 1c. Course stipple, active avalanche paths; light stipple, potential avalanche zones; arrows, small avalanche paths.

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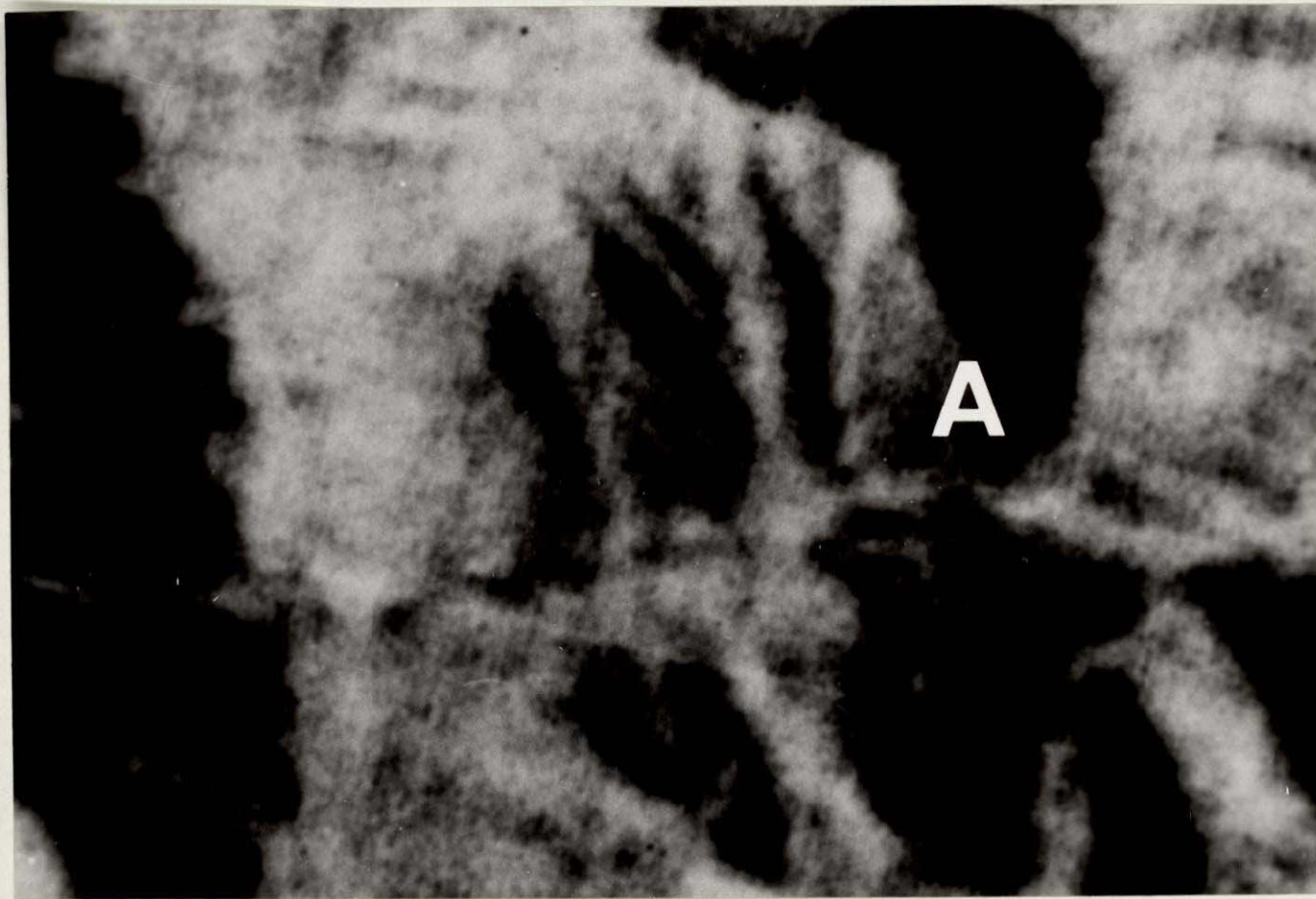


Figure 1c. Enlargement of Landsat image 1425-17190-7 showing the typical appearance of avalanche paths on Landsat imagery. Many of the larger paths are readily apparent, although portions are obscure. Some information has been lost through the photographic reproduction process. Point A is common to Figures 1a, 1b, and 1c.



topographic depression oriented downslope (Fig. 1). These gully avalanches tend to focus the destructive energy of the moving snow towards a relatively small area at the bottom of the avalanche path. Equally dangerous, though more difficult to identify, are avalanche tracks on unconfined slopes (Fig. 2). Because the avalanching snow on unconfined slopes is not centrally focused, the associated avalanche hazard area may be quite extensive compared to the length the avalanche may run. Avalanches attain their maximum velocities and snow depth in the avalanche track (4).

The avalanche runout zone is the area where the snow, rocks, soil, trees, and other debris moved by the avalanche finally come to rest (Fig. 1). The size and shape of the runout zone are directly related to the size and shape of the associated track, although the topographic configuration of the runout zone may exert considerable influence on the detailed area covered by avalanche runout.

A fourth zone, the airblast zone, may sometimes be recognized peripheral to runout zones of high velocity, powder avalanches. Airblast is a gust of wind produced by the movement of avalanching snow that may extend outward from the runout zone for considerable distances. The airblast zone can only be determined from its effects, primarily destructive, on the terrain. Zones of potential airblast should be evaluated in determining the avalanche hazard of an area.

#### CLASSIFICATION

A simple avalanche classification by Fukui (5) considers three properties or characteristics that govern the motion of avalanches:



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Figure 2. Unconfined avalanche hazard slopes in a cirque basin above timberline, San Juan Mountains, southwestern Colorado. Avalanches occur on all slopes in the photo and even in the relatively flat floor of the basin is subjected to avalanche runoff. Yet, there is little direct physical evidence of past avalanche activity. Elevation is approximately 11,500 to 12,500 feet; slopes are mostly between 30 and 45 degrees.



(1) geometrical form, (2) position of the sliding snow relative to the ground surface (slide plane), and (3) snow quality (Table 1).

An avalanche begins with the failure of snow on a slope. The initial motion or release of snow is characterized by one of two geometric forms: (1) point or (2) area. A point avalanche initiates from a point or spot on the slope. As the sliding snow moves downslope from this point, the avalanche path grows wider, so that the entire path has the shape of a V pointing to the point source. Less than a cubic meter of snow may be released in a point avalanche, but more snow is incorporated downslope and a larger avalanche can be triggered. Point avalanches are often referred to as loose snow avalanches because they occur only where snow is relatively cohesionless, e.g. during or immediately after a snowfall (6). Small avalanches, appearing as small trickles on snowy slopes, occur frequently through autumn, winter, and spring.

When cohesive snow fractures and releases simultaneously over an area or region, an area (slab) avalanche occurs. The initial slab of snow may range in volume from about 100 to 10,000 cubic meters (6). After the slab begins to accelerate, it breaks up into small blocks (usually less than a cubic meter) that may entrain additional snow and air as they move downslope. In contrast to a point avalanche, a slab avalanche usually affects larger areas on the slope, travels longer distances, and occurs in a layered or stratified snow that has accumulated over a period of several snowstorms.

The position of the sliding surface controls the flow characteristic of an avalanche. A ground avalanche moves along the ground surface and is more capable of eroding and transporting debris downslope. Topographic features exert an influence on the direction of snow movement and surface

TABLE 1. Classification of Snow Avalanches (5).

		Geometrical Form of Avalanche Rupture		
		Point Rupture	Area Rupture	
Snow quality of avalanche layer	Dry snow	Point-rupture dry-snow surface-layer avalanche	Area-rupture dry-snow surface-layer avalanche	Area-rupture dry-snow total-layer avalanche
	Wet snow	Point-rupture wet-snow surface-layer avalanche	Area-rupture wet-snow surface-layer avalanche	Area-rupture wet-snow total-layer avalanche
		Surface layer		Total layer
		Position of slide plane		

irregularities cause sufficient friction to decrease the velocity of flow..

Surface layer avalanches move on top of a layer of snow and usually attain high velocities because frictional resistance is minimal. Potential slide planes develop when snow metamorphism produces a stratified snowpack in response to temperature and pressure changes. These layers can provide a sliding surface for either slab or point release avalanches. The amount of liquid water within a snowpack is a measure of the snow quality, although no fixed wetness values divide wet and dry snow (6). Dry snow avalanches have little or no interstitial free water within the snowpack. Because of their relatively low density, they tend to follow a straight-line course, flowing over obstacles rather than being deflected or damned. Velocities in excess of 30 meters per second are common and runout distances are greater than wet avalanches.

A powder cloud can develop above the main mass of snow when blocks of snow disintegrate and snow particles are forced high into the air. This airborne cloud of low density material, termed a powder avalanche, can reach velocities of 125 meters per second and produce high impact pressures on obstacles in its path (7). A powder avalanche is not confined to any physical boundary of the path and may extend 100 meters above the general level of the ground (6).

In contrast, wet avalanches have a greater density because of interstitial water. They are deflected by surface irregularities and flow at lower velocities (5 to 30 meters per second) than dry avalanches. As a result, wet avalanches attain shorter runout distances (6), although equally high impact pressures may be generated by the denser snow..

## DIRECT AVALANCHE HAZARD INDICATORS

The problem of delineating avalanche hazard areas involves two types of analysis. The first is concerned with identifying those areas in which avalanches can be shown to have run in the past and, therefore, will probably run again in the future. We must be able to identify characteristics of the terrain that are the direct consequence of avalanching so that the extent of past (and future) avalanche hazards can be estimated. Direct indicators of past avalanche activity can be grouped into two main categories: (1) snow characteristics and (2) vegetation patterns.

A snow characteristic is an identifiable appearance or distribution of the snow caused directly by avalanching. Patches of snow that persist into late spring or early summer, particularly at the base of slopes or at breaks in slope, commonly result from an above average accumulation of snow in avalanche runout zones. Identification of remnant snow patches on forested slopes is an important means of delimiting avalanche hazards in forested terrain.

Linear belts of persistent snow oriented downslope should also be thoroughly studied. They may represent greater-than-average snow accumulations within large avalanche tracks due to successive small avalanches that fail to run to full track. Or, they may exist because they are sheltered from the melting affects of wind, rain, and solar radiation by the topographic configuration of gully-type avalanche tracks.

Actual changes in the character of the snow caused by avalanching during the winter avalanche cycle are rather quickly subdued by wind and

subsequent snowfall. Yet, it is possible to detect patterns of disturbed snow (ridges, grooves, blocks) in the field for a short time after avalanching. Similarly, fracture line scarps produced by slab avalanche release are often selectively shadow enhanced by low sun-angle illumination, and they can be easily seen in the field and on photos.

In the spring, the snow surface acquires wind-transported dust and silt, effectively lowering the albedo of the snow, so that when spring avalanches run, they expose clean snow along their paths. The contact between the dirty, undisturbed snow and the clean snow in the avalanche paths is easily detected in the field and on air photos.

Avalanches commonly have a profound affect on the location and distribution of vegetation, and this relationship provides a powerful and generally applicable set of identification criteria. Perhaps the most conspicuous vegetation pattern attributable to avalanches is the trimline (Fig. 1). A trimline is a sharp break in vegetation caused by the reduction or removal of the natural vegetation within an avalanche path. Trimlines are most obvious where avalanches have cut a swath through mature coniferous forests. The boundaries between forest and forest-free areas are enhanced by moderate snow cover.

Avalanche paths stripped of the larger forms of vegetation may become revegetated if large, full-track avalanches run only infrequently. In the Colorado Rocky Mountains, revegetation of avalanche paths cut through coniferous forests is most commonly by aspen (*populus tremuloides*). Aspen intergrown with conifers can be readily discriminated, however, the overall pattern of these vegetation intergrowths must be carefully evaluated because aspen reforestation can be triggered by phenomena other than avalanches. Occasional recurrence of avalanche activity

may produce several stages of aspen reforestation that can be detected in the field by differences in tree height and crown diameter. An avalanche may move through forested terrain without removing the trees, although some tree damage may occur. Similarly, trees may be damaged along the lateral margins of avalanche paths and in airblast zones. The damaged trees are less vigorous than surrounding undamaged trees, and this condition can often be detected.

#### INDIRECT AVALANCHE HAZARD INDICATORS

The second, and most difficult, type of avalanche hazard analysis involves the identification of areas in which avalanches may occur in the future, but which cannot be shown to have been active in the past. These areas contain no direct indicators of past avalanche activity, such as trimlines. Indicators that suggest the possibility of avalanche hazard are of two types: (1) topographic and (2) vegetative.

No single topographic feature is indicative of possible avalanche hazard. To the contrary, landform analysis that considers the sum of many topographic phenomena is necessary to confidently define potential avalanche hazard areas. Comparison of the topographic character of active avalanche areas with "unknown" terrain is an invaluable interpretive aid.

The following is a general list of the topographic factors of the terrain that must be evaluated:

- (1) slope angle - steep enough to promote movement, but gentle enough to allow the accumulation of snow;  
30° to 45° slopes most common.

- (2) slope aspect - the orientation of the slope with respect to the sun and prevailing winds.
- (3) relief - the potential vertical drop.
- (4) slope profile - both longitudinal and transverse should be evaluated.
- (5) elevation - must be high enough to receive heavy winter snowfall.

The absence of substantial vegetation, whether natural or artificial may indicate a potential for avalanching. Isolated patches of vegetation-free ground on otherwise well-vegetated slopes may mark potential avalanche starting zones characterized by yearly, greater-than-average snow depths. Deforestation caused by forest fires is a particularly important aspect of avalanche hazard analysis because it may produce an avalanche hazard in an area that was previously considered safe. Completely non-forested slopes must be studied very carefully, since the absence of trees (anchor points for snowpack) may contribute to the instability of the winter snowpack. The absence of trees, however, is not sufficient for defining an avalanche hazard area; vegetation anomalies must be evaluated in relation to the topographic configuration of the terrain.

## LANDSAT MAPPING PROGRAM

The most difficult task in this investigation was to develop a reliable method of defining avalanche hazards regionally. Preliminary attempts using LANDSAT-derived information alone proved unsatisfactory. So, a method combining information from published avalanche maps, LANDSAT imagery interpretation, and analysis of small-scale topographic maps (1:250,000) was developed. This method was tested in control areas and found to be reasonably consistent and accurate.

### PRELIMINARY MAPPING

The LANDSAT-derived avalanche hazard mapping technique adopted in this investigation evolved through a series of trial-and-error attempts. Two lines of investigation were concurrently pursued: (1) determine which direct and indirect avalanche indicators can be identified on LANDSAT imagery and (2) test various mapping schemes in relatively small control areas.

LANDSAT images of the San Juan Mountains, southwestern Colorado, were studied to see which of the avalanche indicators are detectable on the imagery and to what degree these indicators can be identified using conventional photointerpretation techniques on the black and white, 1:1,000,000-scale positive transparencies, as well as photographic enlargements of these transparencies. In general, direct avalanche indicators, including snow characteristics and vegetation patterns, cannot be consistently interpreted from the imagery. Evidence of avalanching contained in the distribution of snow (lingering patches of snow in runout zones and tracks on spring and early summer imagery) is generally too small to be identified, although a few instances were noted. No evidence of dynamic snow movements were



detected on any of the consecutive-day images studied.

Vegetation anomalies characteristic of avalanche areas are likewise difficult to identify with certainty. The largest and most dramatic vegetation anomaly associated with avalanches, the trimline, was identified in several areas, but other well-known trimlines could not be identified. The difficulty arises because of three factors: (1) trimlines are commonly on valley slopes and these slopes are often in shadow; (2) many avalanche paths defined by sharp trimlines are too small to be adequately resolved on the imagery; (3) forest/non-forest boundaries resulting from other natural and man-made causes are easily mistaken for trimlines (the opposite also applies).

Better and more consistent results were produced by evaluating the LANDSAT images for indirect indicators of avalanche-prone areas. Of these, topographic indicators, including slope angle, aspect, and profile and topographic relief are the most useful. Topographic analysis of the LANDSAT images, however, is most effective where stereoscopic interpretation can be performed using consecutive-day images. Without the stereoscopic model, the preliminary interpretations were tenuous. Pseudostereoscopic analysis using two bands of the same scene for a stereopair does give a perception of the third dimension, but the vertical exaggeration is too slight to allow confident interpretation.

The initial attempt at avalanche hazard mapping used indirect indicators as the main source of avalanche hazard information, with direct indicators supplementing the topographic interpretations where possible. Both stereoscopic and monoscopic analyses were conducted on 1:1,000,000-scale transparencies and 1:250,000-scale enlargement prints. Both band 5 and 7 images were interpreted, although all four bands were inspected. Band 5 has somewhat better contrast, often making the boundaries of

avalanche paths easier to map. But less than 2% more paths could be mapped on band 5 images than on band 7. Individual avalanche paths and areas of probable avalanching were delineated on clear acetate overlays, and the results were compared to detailed 1:24,000-scale avalanche hazard maps of the test area previously prepared by INSTAAR under NASA Grant NGL 06-003-200. A total of 108 paths were mapped on the detailed maps and 86 were mapped from LANDSAT imagery. Of the 86 mapped on LANDSAT, 24 were not mapped on the detailed maps. If it is assumed that the detailed maps show the actual number and location of avalanche paths in the test area, then the results of the LANDSAT imagery interpretations can be summarized as follows:

(1) 57% (62/108) of the avalanche paths in the test area were correctly identified and mapped.

(2) 72% of the avalanche paths mapped on LANDSAT imagery are actually avalanche paths, and 28% were incorrectly identified as avalanche paths.

Although this mapping exceeded original expectations, the method had two serious defects: (1) Individual avalanche paths could not be consistently identified and some avalanche hazard areas were shown as avalanche-free (this is the worst possible error in avalanche hazard mapping) and (2) the mapping subdivisions were too broad to be very useful.

Therefore, a revised scheme was developed to acquire more consistency and insert a range of hazard levels into the hazard maps. To achieve more consistency, attempts to map all individual avalanche paths were abandoned in favor of defining areas of similar avalanche hazard potential. This scheme classifies all areas according to the maximum size of potential avalanches that might be expected; implicit in the classification is the fact that avalanches smaller than the maximum would also be expected.

The size classification (Table 2 ) is based on the work of Frutiger (8) and is determined by the maximum area of potential starting zones or catchment basins that could conceivably release at one time.

<u>SIZE CLASSIFICATION</u>	<u>AREA OF STARTING ZONE</u>
avalanche-free	0
small	7 acres
medium	7 to 30 acres
large	30 acres

Table 2 . Classification of maximum potential full-track avalanche based on area of starting zones.

To determine the size of potential avalanches using the LANDSAT imagery, templates were constructed for 7 and 30 acre areas. Since the starting zones are sloping surfaces, the actual areas of the templates were adjusted to represent these areas on a 45 degree slope. This is somewhat greater than the average slope, but it is better to overestimate the size of potential avalanches than underestimate them. The area of the potential starting zones were interpreted on the LANDSAT imagery, measured by comparing to the templates, and classified into the appropriate category. The resulting map, then, shows broad areas of similar maximum avalanche sizes within which smaller avalanches are presumed to occur.

Although this method successfully achieved a stratification of hazard levels, it also proved to be too general. Furthermore, it did not take advantage of the level of avalanche hazard detail (albeit inconsistent)

that can be extracted from the LANDSAT imagery. The basic problems with this method were the inability to consistently identify starting zones (no improvement over previous method) and the difficulty in estimating the size of starting zones on unconfined slopes. Some avalanche hazards falling into the "large" category were not identified on the LANDSAT imagery, mainly because they occur on shadowed, north-facing slopes. However, the cumulative error caused by missing "small" and "medium" avalanche zones was much more serious. There appeared to be no terrain factors responsible for disguising these zones on the imagery; they are readily identifiable on 1:30,000-scale color infrared photos. It was concluded that the LANDSAT imagery system was merely unable to resolve enough detail to allow these avalanche zones to be interpreted.

This preliminary avalanche hazard mapping represents the first attempt to systematically define avalanche hazards on LANDSAT imagery, and several important conclusions can be drawn from the results of the exercise:

- (1) Avalanche hazard mapping on LANDSAT imagery must rely heavily upon the interpretation of indirect indicators of avalanche activity.
- (2) Many avalanche hazard zones are too small, or the physical evidence of avalanching is too diffuse (or completely lacking) to be adequately resolved by the LANDSAT system.
- (3) Avalanche hazard zones have no unique spectral reflectance characteristics that would be compatible with automatic classification techniques.
- (4) Photointerpretation of standard, single-band, LANDSAT images (1:1,000,000 transparency and 1:250,000 prints) is insufficient for preparing a reliable regional avalanche hazard map of even modest detail.

## MAPPING WITH SUPPLEMENTAL DATA

Results of the preliminary studies indicated that the regional mapping of avalanche hazards cannot be satisfactorily accomplished from LANDSAT imagery alone. However, the interpretation of LANDSAT imagery, integrated with readily-available supplementary information, provides a much sounder base for regional avalanche hazard mapping. A procedure for using selected supplementary information in conjunction with LANDSAT imagery was developed and has been applied to regional avalanche hazard mapping in the Colorado mountains. The procedure consists of three steps that overlap and reinforce each other: (1) gross delineation of potential avalanche terrain (topographic analysis); (2) interpretation of avalanche terrain (LANDSAT imagery analysis); (3) identification of avalanche terrain (published avalanche maps).

Potential avalanche terrain is defined as terrain that has a topographic configuration that will promote avalanching when suitable meteorological and vegetation conditions are established. The variables, mainly the amount of precipitation as snow, temperature and temperature variations, and wind velocity and direction (meteorological) and the presence or absence of mature forest (vegetation), can be approximated regionally by considering elevation above sea level. However, it should be noted that natural and man-induced events may significantly alter the "normal" environment of an area from time to time. The delineation of potential avalanche terrain, then, consists of (1) defining those areas, which by virtue of their elevation, most probably have suitable meteorological and vegetation characteristics for the development of avalanches and (2) restricting the areas defined in (1) to only those areas that have a suitable topographic configuration (relief or slope) for

avalanches to run. This type of mapping can be accomplished by analyzing topographic maps; the detail and accuracy attained is a function of the scale and vintage of the topographic maps.

#### Topographic Analysis

Based on the work by Frutiger (8) and detailed avalanche hazard mapping by INSTAAR personnel (NASA Grant NGL 06-003-200) in the Colorado mountains (9, 10, 11, 12), the number of avalanches that occur is sensitive to elevation. Avalanches are uncommon below approximately 9,000 feet; between 9,000 feet and 12,000 feet the number of avalanche occurrences becomes significant. Above 12,000 feet, avalanches are much less common, except for loose snow sloughing, because these areas are above timberline and are steep and exposed to high winds that tend to restrict the accumulation of snow. These studies have also shown that most avalanches in Colorado occur on slopes between 22 and 45 degrees.

Using these general avalanche characteristics, a first approximation of regional avalanche hazards can be prepared by analyzing suitable topographic maps. For this investigation, the 1:250,000-scale topographic quadrangles of montane Colorado were used to define all areas above 9,000 feet elevation that have slopes steeper than 22 degrees. These slopes, which are indicative of potential avalanche hazard areas, were defined on the topographic maps by both visual and computer methods. The two methods were compared to determine the best method of slope evaluation in terms of accuracy and economy.

The first method of delineating slopes greater than 22 degrees was by visual inspection of contour spacings (1:250,000 topographic map) using a 22-degree contour spacing template as a guide. Slopes greater than 45 degrees were not differentiated because the contours are too close together to accurately measure. The alternative method used

a computer to generate slope maps from digitized topographic data available from the Defense Mapping Service (1:250,000) . The U.S. Forest Service in Fort Collins, Colorado, prepared the slope maps. For every eighth slope-data point, the computer generated an approximation of the mean slope using the 8 nearest points (about 3.2 hectares). Better accuracy could have been obtained by computing the slope more frequently, but the cost would have risen significantly. Slope categories of less than 22 degrees, 22- to 45-degrees, and greater than 45 degrees were defined.

The Spar City 15' quadrangle (1562.9 hectares) within the Durango 1:250,000 topographic quadrangle was used as a test area to compare the two methods (Fig. 3). As shown in Table 3, 79% of the area is in agreement if the computer categories are restructured into greater than and less than 22 degrees so a comparison can be made. However, in 21% (328.2 hectares) of the total area, the two slope mapping methods did not agree. A simple test was conducted to determine what portion of the total area of disagreement was correctly mapped by each method. A point was randomly selected in each of 40 uniformly-sloping areas where the mapping did not agree, and the slope steepness was determined in the vicinity of each point by measuring the contour spacing on the topographic map (1:62,500). The results summarized in Table 3 show that the computer was correct in 82.1 hectares (5% of the quadrangle area) of the area of disagreement and the visually constructed slope map was correct in 172.3 hectares (11% of the quadrangle area). The area represented by the remaining 73.8 hectares is composed of many small areas (less than 0.3 hectares) in which the slope rapidly changed steepness. Within each of these areas, there are slopes that fit into both the visual and computer-generated slope map classifications, and neither can be considered



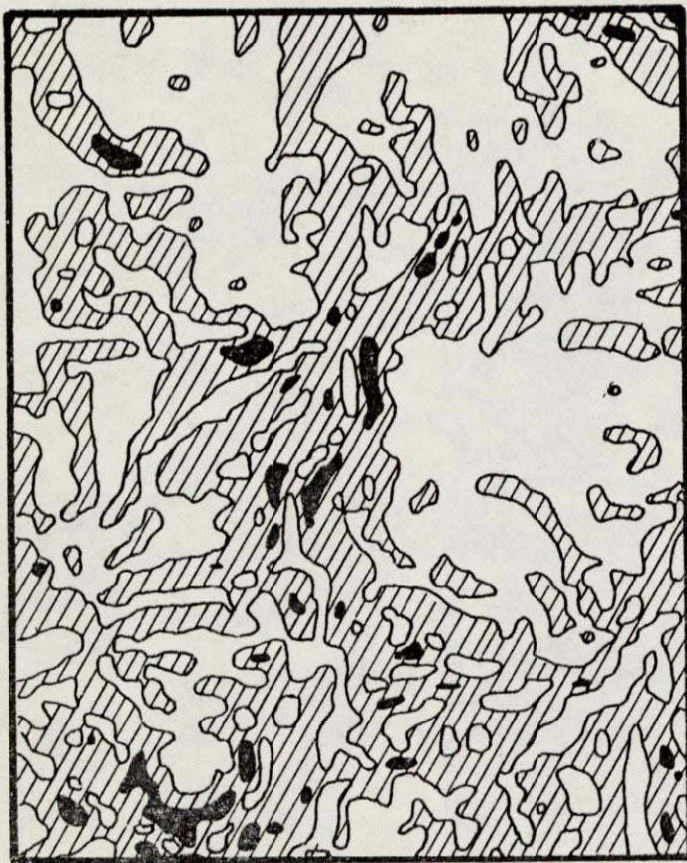


Fig. 4a. Computer-generated slope map of Spar City quadrangle, Colorado. Black, greater than 45 degrees; cross-hatch, 22- to 45-degrees; blank, less than 22 degrees.



Fig. 4b. Slope map visually interpreted using a contour spacing template. Cross-hatch, greater than 22 degrees; blank, less than 22 degrees.





Fig. 4c. 1:250,000-scale topographic map of the Spar City quadrangle, Colorado. Contour interval 200 feet.

	COMPUTER MAP		VISUAL MAP		SUMMARY	
	% total area correct	area (hectares)	% total area correct	area (hectares)	%	area
AREA OF AGREEMENT	79	1234.7	79	1234.7	79	1234.7
		one method correct	5	82.1	11	172.3
AREA OF DISAGREEMENT						
		SUBTOTAL	84	1316.8	90	1407.0
					21	328.2
		both methods correct	5	73.8	5	73.8
TOTAL	89	1390.6	95	1480.8	100	1562.9

Table 3 . Comparison of the accuracy of computer- and visually-generated slope maps prepared for the Spar City quadrangle (1:62,500), southwestern Colorado.

totally correct or totally incorrect.

As discussed previously, slopes steeper than 45 degrees are relatively low avalanche hazards because they are incapable of retaining a thick snowpack. Consequently, separating these slopes from those between 22 and 45 degrees would provide at least a crude definition of low and high avalanche hazards, respectively. Slopes steeper than 45 degrees could not be adequately defined by visual interpretation of the 1:250,000-scale topographic base maps used for the avalanche hazard mapping, but these slopes were delineated on the computer-generated slope maps. To check the accuracy of the computer mapping and determine the possible significance of omitting these slopes on the visually-prepared map, an analysis was conducted using the Spar City quadrangle for the test area. Results of the study are summarized in Table 4. The computer delineated a composite area of 24 hectares (1.5% of the total quadrangle area) as having slopes steeper than 45 degrees. Slope measurements made from the 1:62,500 topographic map showed that 20 hectares of the 24 hectares defined actually have slopes steeper than 45 degrees; the remaining 4 hectares slope less than 22 degrees. No rigorous attempt was made to determine how many slopes steeper than 45 degrees were missed by the computer mapping, but inspection of the topographic map suggests that there are few, if any, that could be outlined at a scale of 1:250,000. By contrast, the slope map prepared by visual interpretation correctly showed the 20 hectares as sloping greater than 22 degrees and also correctly identified 2.7 hectares of the 4 hectares sloping less than 22 degrees that were missed by the computer. Accuracy of the visual maps is 94.5% (22.7 of 24 hectares), although the mapping categories are much broader.

<u>ACTUAL SLOPE</u>	<u>VISUAL INTERPRETATION</u>	<u>AREA(Hectares)</u>
45	22	20.0
22	22	2.7
22	22	1.3

Table 4 . Analysis of 24 hectares mapped by computer as having  
slopes steeper than 45 degrees.

Because the area having slopes steeper than 45 degrees is small (29 hectares within 1562.9 hectares), the absence of this category from the visually prepared maps does not appear to be serious, particularly at the scale of 1:250,000. These slopes were correctly identified in the greater than 22 degree slope category. From an economic standpoint, the computer maps cost \$120 for each 2-degree quadrangle (1:250,000) and take approximately 1 hour to prepare. This compares with visual slope maps which took 8 hours to prepare and cost approximately \$32 to \$64 depending on hourly wages.

The visual inspection method of slope analysis has better overall accuracy and only costs one-half to one-fourth as much as the computer-generated maps. However, the computer-generated maps take one-eighth the time, and can identify slopes steeper than 45 degrees with reasonable accuracy. The omission of slopes steeper than 45 degrees on the visually interpreted maps is not serious, since these slopes are such a small portion of the total area (approximately 1%). Both methods can be satisfactorily applied to delineating the potential for avalanche hazards at a scale of 1:250,000. Choosing the best method for a particular mapping program depends on whether or not the higher cost/quicker turn-around of the computer method is justified. For this investigation, we elected to use the visual interpretation method because of its lower cost and somewhat better reliability. Slope maps were prepared for the Leadville, Montrose, and Durango 1:250,000 quadrangles covering a large portion of mountainous Colorado. These maps show potential avalanche zones based on the elevation (meteorologic factors) and character of the terrain, alone. The reliability of this mapping was extensively tested and will be discussed in a later section.

### Interpretation of LANDSAT Imagery

The potential avalanche terrain described in the previous section mostly represents slopes on which avalanches could be initiated by extremely heavy snowfall or the removal of anchor points that currently tend to stabilize the snowpack. No evidence of active avalanche activity has been detected in these areas, although detailed testing of the mapping method, described later in this report, indicates that some of the potential avalanche terrain does undergo periodic avalanche activity. On the regional avalanche hazard maps, then, potential avalanche terrain is the lowest level of avalanche hazard that has been defined.

The next highest level of avalanche hazard is avalanche hazard zones interpreted from LANDSAT imagery. These zones are recognized by interpreting direct and indirect indicators of past avalanche activity on the imagery. Therefore, they take precedence over the more general category of potential avalanche hazards.

Numerous methods and imagery formats were employed to determine the most useful approach for mapping avalanche hazards on LANDSAT imagery. As reported earlier, single-band (mostly bands 5 and 7), black and white positive transparencies (1:1,000,000) are too small-scale to permit annotation of many avalanche zones that can be recognized. Consequently, actual mapping was conducted on 1:250,000-scale enlargement prints. The transparencies, however, are better quality than the prints, and they were routinely used in conjunction with the enlargement prints.

Initial image interpretations were conducted over areas where consecutive-day images provided sidelay suitable for stereoscopic analysis. Subsequent interpretations of areas without the benefit of the stereoscopic

model proved difficult because apparently anomolous vegetation patterns could not be satisfactorily placed in their topographic setting, rendering the interpretation of avalanche paths tenuous. For LANDSAT imagery of central Colorado, approximately 60% of each image is not overlapped by previous- or following-day imagery, and stereoscopic analysis is not possible. Considering the importance of being able to evaluate topography, as well as tonal and textural patterns, an alternative method of relating the imagery to the actual topography was pursued. Pseudostereoscopic analysis using band 5 and 7 images of the same scene as a stereopair was tried. A small three-dimensional effect is achieved, but the vertical exaggeration is too small to permit an accurate and consistent evaluation of topography. The possibility of using computer-generated LANDSAT stereopairs using the technique developed by Batson, Edwards, and Eliason ( 13 ) at the U.S. Geological Survey was explored, but Mr. Batson informed us that the technique was still very experimental, needed sophisticated processing equipment, and would be very expensive. It was decided that the LANDSAT interpretations would have to be continuously referenced to available topographic maps in order to avoid the ambiguities discovered during non-stereoscopic analysis.

Since the 1:250,000-scale topographic quadrangles were used to prepare the potential avalanche hazard maps satisfactorily, these maps were also used for topographic reference during LANDSAT imagery interpretations. Initially, 1:250,000, black and white LANDSAT prints of band 5 or 7 were placed on a light table and overlain by a paper copy of the appropriate 1:250,000 topographic map; interpretations were plotted directly on the map. Registration of the prints and maps was better than expected, with

approximately 50% to 60% of the map capable of being suitably registered at one time. Backlighting of the prints and maps was sufficient to allow registration and some interpretation in a darkened room, but for the more difficult areas, it was necessary to lift a corner of the overlying map to study the print directly. Continuous reference was also made to the 1:1,000,000 positive LANDSAT transparencies during all interpretations. Since the method proved effective, copies of the 1:250,000 topographic quadrangles printed on a physically-stable frosted mylar base were acquired and routinely used for the bulk of the LANDSAT imagery interpretations. This eliminated the necessity of removing the topographic map to see the print more clearly.

Both summer and winter imagery were investigated for evidence of snow avalanche hazards (Fig. 4). Topography was generally better depicted on the low sun-angle winter scenes, but the proportionally larger area of shadows and the inability to distinguish snow characteristics related to avalanching cancelled the potential usefulness that was anticipated. Snow-free imagery, however, contained the information on the type and distribution of vegetation that is essential for avalanche hazard mapping on LANDSAT imagery, and when used in conjunction with the 1:250,000 topographic maps, provides a good data base for regional mapping.

The importance of being able to identify and map characteristic vegetation patterns prompted the examination of 1:250,000 false color (color infrared) composites made from bands 4,5, and 7 at the U.S. Geological Survey EROS Data Center in Sioux Falls, South Dakota. A comparison between the color composite and the black and white image from band 7 of the same scene was conducted to determine if avalanche hazard zones could be more easily and accurately mapped on the color composites. The area covered





19 November 1972 (1119-17204-7)  
SNOWFREE



27 October 1973 (1461-17181-5)  
SNOW COVERED

Figure 4. Snowfree and snow covered LANDSAT imagery of the central San Juan Mountains, Colorado, near Silverton, Colorado. Arrow points to the area shown in Figure 1.

by the adjoining Mount Sneffles and Ouray 1:24,000 quadrangles (Montrose 1:250,000 quadrangle) was chosen for a test area because detailed, 1:24,000 avalanche hazard maps are available for the area (11) and the area had not been previously interpreted on LANDSAT imagery during this investigation. An avalanche hazard map of the test area was prepared from the 1:250,000 black and white, band 7 print and also from the color composite print using the technique described above. A 10 by 19 grid was constructed on the detailed reference map and the two LANDSAT-derived hazard maps. Each grid point intersection (190 total) was then classified as either avalanche hazard or avalanche-free, and the results were compared for accuracy and completeness. The results are summarized in Table 5. Three times as many known avalanche hazard zones were correctly mapped on the color composite compared to the black and white image. But in both cases, the percentage of the total known avalanche zones determined from the detailed map was small (27% and 9%, respectively). Results of this test clearly illustrate that the interpretation of LANDSAT imagery alone is insufficient for preparing an accurate, and more importantly, complete avalanche hazard map. However, the results of the testing of the complete mapping method described in the following section, shows that a good quality map can be prepared if supplemental data are used in conjunction with LANDSAT imagery interpretations. The fact that only two common avalanche hazard points were shared between the two LANDSAT-derived hazard maps indicates that it may be necessary to use both types of imagery to obtain the maximum amount of information. However, only a small loss of information occurs if only the color composite is used.

LANDSAT IMAGERY			
		Color Composite	Black and White
	Total Mapped*	12	4
INTERPRETED	Correctly Mapped	9 (75%)	3 (75%)
AVALANCHE	Actually Potential	2 (16.7%)	1 (25%)
HAZARD	Avalanche Zones		
	Actually Avalanche	1 (8.3%)	0
ZONES	Free		
% KNOWN AVALANCHE ZONES		27 (9/33)	9 (3/33)
CORRECTLY MAPPED			

\* Only 2 points were identified on both types of imagery.

Table 5. Comparison of avalanche hazard zone mapping on 1:250,000 LANDSAT color composite and black and white, band 7 prints to detailed (1:24,000) avalanche hazard maps of the Mount Sneffles and Ouray quadrangles, southwestern Colorado (Montrose 1:250,000 topographic quadrangle). Landsat image E-1407-17191 was used for the comparison.

### Compilation of Existing Avalanche Hazard Maps

The final phase of regional avalanche hazard mapping for this investigation consists of compiling existing, detailed avalanche hazard mapping on to the 1:250,000 topographic base maps. This mapping has the highest priority since it identifies "known" avalanche hazard zones, usually at a scale of 1:31,680 or larger, as determined through detailed analysis of relatively restricted areas. Passage of Colorado House Bill 1041 in 1974, requiring Colorado counties to prepare geologic and snow avalanche hazard maps for those portions of the counties under county jurisdiction, has stimulated the preparation of avalanche hazard maps in the state. Much of this work has been conducted by INSTAAR under NASA Grant NGL 06-003-200. Even so, only an extremely small portion of the Colorado mountains has been adequately mapped. As more detailed avalanche hazard maps become available, the regional avalanche hazard maps prepared for this investigation can be periodically updated with relative ease because the known avalanche hazard zones have precedence over the potential and interpreted hazard zone mapping categories.

### Evaluation of Mapping Method

During the early phase of this investigation, subjective visual comparisons between detailed (1:24,000) avalanche hazard maps and LANDSAT imagery indicated that many known avalanche paths are well-expressed on the LANDSAT imagery. However, as the study progressed to the actual mapping stage, it became apparent that some known paths could not be detected on the imagery and that some avalanche-free areas were being incorrectly interpreted as avalanche hazard zones on the LANDSAT imagery. Therefore, tests were conducted to determine the accuracy and reliability of the final maps.

The area covered by three 7.5-minute (1:24,000) quadrangles in the San Juan Mountains of southwestern Colorado was selected for the control area (Fig. 5). The snow avalanche hazards in these quadrangles (Ouray, Mount Sneffles, and Sams) were mapped in detail by INSTAAR as part of a program to map geologic and avalanche hazards in Ouray County, Colorado, under NASA Grant NG-L 06-003-200 (11).

Control data points were established uniformly over each quadrangle by constructing a 10 x 10 grid (100 points per quadrangle). The avalanche hazard (active, potential, or avalanche-free) was then tabulated for each unique data point, so that the detailed and LANDSAT mapping could be correlated point-for-point. The LANDSAT imagery of each quadrangle was interpreted for avalanche hazards and these interpretations were combined with the slope maps (potential avalanche zones) to produce an avalanche hazard map showing interpreted and potential avalanche hazards at a scale of 1:250,000. A 10 x 10 grid was constructed for each quadrangle, and the

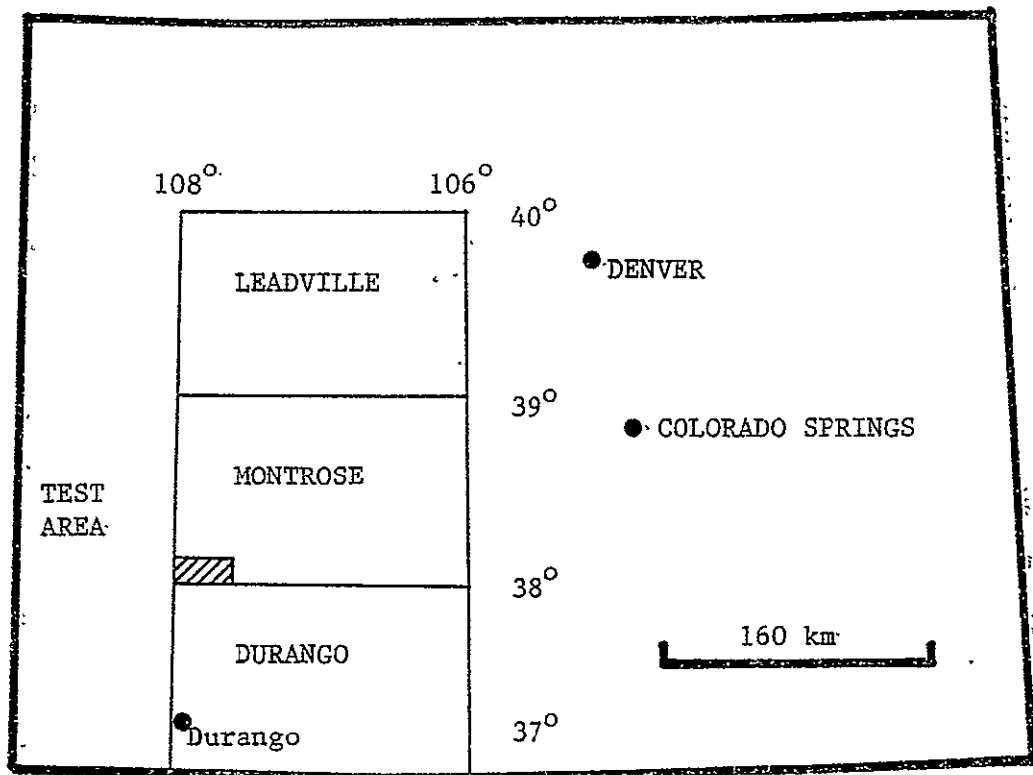


Figure 5. Index map of Colorado showing the location of the Leadville, Montrose, and Durango 2-degree (1:250,000) quadrangles and the 3-quadrangle mapping evaluation test area.

avalanche hazard category at each grid point intersection (interpreted, potential, or avalanche-free) was tabulated for comparison with the detailed mapping category at the same point.

The results of the comparison with the detailed mapping in each quadrangle is shown in Tables 6, 7, and 8. Table 9 summarizes the comparison for the three-quadrangle area. The percentages of avalanche free, potential, and active avalanches are determined by 300 sample points from the detailed mapping (73.7, 11, and 15.3 respectively) of the three-quadrangle area appears to be very close to visual estimates made from inspection of the maps. This suggests that the 300 point sample is sufficient for comparing the detailed and LANDSAT-derived avalanche hazard maps. For the entire three-quadrangle area (Table 9), 57.6% of the sample points are in perfect agreement on the classification of avalanche hazards, but for 42.4% of the points there is disagreement. Since the detailed maps were prepared by large-scale air photo analysis and field investigation, it must be assumed that they are correct. Therefore, the observed disagreement must be due to errors in the LANDSAT-derived mapping. The errors are of two types (Table 9): (1) errors of over-estimation and (2) errors of under-estimation. Errors of over-estimation occur where the hazard defined on the LANDSAT-derived map is greater than the actual hazard. These errors occurred in 23.3% of the sample points and are all errors in which the LANDSAT-derived mapping defined a potential avalanche hazard in an avalanche-free area. This type of error is not particularly serious, since it does not create a false sense of safety, as in errors of underestimation. Nor is it particularly surprising considering the low topographic resolution possible on the 1:250,000-scale topographic maps used to define the potential avalanche hazards.

Table 6. Comparison of LANDSAT-derived and detailed avalanche hazard mapping in the Ouray quadrangle, southwestern Colorado. 100 test points sampled.

		LANDSAT-DERIVED MAPPING			Total
		Avalanche Free	Potential	Inter- preted	
Detailed Mapping	Avalanche Free	37	21	0	58
	Potential	7	20	0	27
	Active	0	15	0	15
Total		44	56	0	100

Table 7. Comparison of LANDSAT-derived and detailed avalanche-hazard mapping in the Mount Sneffles quadrangle, southwestern Colorado. 100 test points samples.

		LANDSAT-DERIVED MAPPING			Total
		Avalanche Free	Potential	Inter- preted	
Detailed Mapping	Avalanche Free	50	27	0	77
	Potential	3	2	0	5
	Active	0	18	0	18
Total		53	47	0	100






Table 8. Comparison of LANDSAT-derived and detailed avalanche hazard mapping in the Sams quadrangle, southwestern Colorado. 100 test points sampled.

		LANDSAT-DERIVED MAPPING			Total
		Avalanche Free	Potential	Inter- preted	
Detailed Mapping.	Avalanche Free	64	22	0	86
	Potential	1	0	0	1
	Active	0	13	0	13
Total		65	35	0	100

Table 9. Summary of comparisons of detailed and LANDSAT-derived avalanche hazard mapping of the Ouray, Mount Sneffles, and Sams quadrangles, southwestern Colorado. 300 data points sampled; percentages shown in parenthesis.

		LANDSAT-DERIVED MAPPING			Total
		Avalanche Free	Potential	Inter- preted	
Detailed Mapping	Avalanche Free	151 (50.3)	70 (23.3)	0 (0)	221 (73.7)
	Potential	11 (3.7)	22 (7.3)	0 (0)	33 (11)
	Active	0 (0)	46 (15.3)	0 (0)	46 (15.3)
Total		162 (54)	138 (46)		300 (100)

	Errors of underestimation (19%)
	Agreement; no error (57.6%)
	Errors of overestimation (23.3%)

Errors of under-estimation occur when the LANDSAT-derived mapping shows the avalanche hazard to be less than is actually the case, such as mapping a potential avalanche hazard in an active avalanche zone. For the test mapping area, 57 (19%) of the 300 sample points had errors of under-estimation (Table 9). These errors are of some concern, since they do misrepresent the seriousness of the snow avalanche threat. However, the possible errors of under-estimation do not all represent the same level of misrepresentation. The error involved in incorrectly mapping a known, active avalanche zone as avalanche-free is the most serious type of error that can occur. For obvious reasons, a mapping method that would allow even a small percentage of this type of error is unacceptable. No errors of this type are included in the 19% error of under-estimation discovered during evaluation of the mapping method in the three-quadrangle test area. The least important error of under-estimation occurs when known, active avalanche zones are incorrectly mapped as potential avalanche hazards. This type of error occurs in 46 (15.3%) of the 300 sample points tested, illustrating the difficulty in interpreting avalanche hazard zones on LANDSAT imagery. However, in terms of the regional mapping for this investigation, these errors have been effectively cancelled by stating in the definition of potential avalanche hazard zones that this category includes some active avalanche zones that could not be detected on LANDSAT imagery. Although this reduces the level of exactness of the potential avalanche hazard mapping category, this is not regarded as a significant fault because of the inevitable generalizations that must be made when mapping avalanche hazards at a scale of 1:250,000.

An intermediate error of under-estimation occurred in 11 (3.7%) of the 300 test points, when potential avalanche hazard zones were incorrectly mapped as avalanche-free. The source of the error can be directly traced to the

criteria for defining potential avalanche hazard zones: (1) slopes steeper than 22 degrees and (2) elevation above 9,000 feet. Each of the 11 points where this type of error occurred was examined to determine why the error was made. In each case, the slopes are steeper than 22 degrees, so the error cannot be attributed to an inability to estimate slope steepness. However, 9 of the 11 points are below 9,000 feet elevation and the remaining 2 points are at approximately 9,000 feet elevation and lie very close to the potential avalanche/avalanche-free boundary constructed on the map. The two error points at 9,000 feet elevation can be explained by spacial differences between the 1:250,000 and 1:24,000 topographic maps. Detailed maps of the three-quadrangle test area were prepared under the assumption that 7,000 feet elevation is the best low elevation cut-off for potential avalanches, and it seems to work well in this area. This suggests that lowering the low elevation cut-off for potential avalanche hazards on the LANDSAT-derived avalanche hazard maps could eliminate most, if not all, of this type of error of under-estimation. Lowering the low elevation cut-off from 9,000 feet to 8,500 feet elevation, for example, would eliminate 7 of the 11 errors of under-estimation. However, inspection of detailed avalanche hazard mapping from other areas indicates that lowering the cut-off elevation to 8,500 feet would cause a substantial increase in errors of over-estimation of the type where avalanche-free areas are incorrectly mapped as potential avalanche hazard zones. Consequently, the 9,000-foot elevation cut-off was retained and the 3.7% error accepted as a characteristic of the mapping method. Future regional avalanche hazard mapping programs could benefit by allowing for the time and funding necessary to establish the low elevation cut-off elevation for potential avalanche hazards in several sectors of the region. This would probably have to be accomplished through a field investigation program because detailed avalanche hazard maps are likely to be sparse or non-existent.

## SUMMARY

Many avalanche hazard zones can be identified on LANDSAT imagery, but not consistently over a large region. Therefore, regional avalanche hazard mapping using LANDSAT imagery must draw on additional sources of information and analyses. A method was devised that depicts three levels of avalanche hazard according to three corresponding levels of certainty that active avalanches occur (Table 10). The lowest level, potential avalanche hazards, are defined by delineating slopes steep enough to support avalanches at elevations where snowfall is likely to be sufficient to produce a thick snowpack. For this investigation, slopes steeper than 22 degrees at 9,000 feet elevation or higher were used to define potential avalanche zones. The accuracy of potential avalanche hazard mapping can probably be improved by independently establishing the low elevation cut-off in several sectors of the region, rather than applying a single cut-off elevation over the entire region. Many active avalanche zones not detectable on LANDSAT imagery and not mapped in detail during previous studies occur in the mapped potential avalanche hazard zone.

The intermediate level of avalanche hazard is interpreted avalanche hazard zones. These are zones in which direct and indirect indicators of active avalanche activity have been interpreted from LANDSAT imagery. Subjective comparison of LANDSAT-derived avalanche hazard zones with detailed mapping conducted by air photo interpretation and field studies indicates that most of the LANDSAT interpretations are active avalanche zones, but many active avalanche zones are not interpreted and, consequently, are included in the potential avalanche hazard zones. False color (color IR) enlargements (1:250,000) of the LANDSAT imagery are the overall best type of imagery for interpreting avalanche hazards, although a very slight improvement can be gained by using a 1:250,000

INCREASING RELIABILITY  
↓

MAPPING CATEGORY	DEFINITION	SOURCE OF INFORMATION
Potential Avalanche Zone	Slopes steeper than 22 degrees occurring above 9,000 feet above sea level	1:250,000 topographic maps (U.S. Geological Survey)
Interpreted Avalanche Zone	Areas on LANDSAT imagery displaying direct or indirect indicators of past avalanche activity	Single-band and color composites of 1:1,000,000 and 1:250,000 LANDSAT imagery and 1:250,000 topographic maps
Active Avalanche Zone	Areas of active avalanche activity determined from field studies and air photo analysis	Existing avalanche hazard maps at scales of 1:24,000 or larger

Table 10. Summary of the snow avalanche hazard classification used for regional (1:250,000) mapping in the central Colorado mountains.

print of band 7 or 5 in conjunction with the false color image. Since topography is such an important factor in avalanche hazard interpretation on LANDSAT imagery, the lack of stereo overlap on approximately 60% of each image is a serious problem. We found that a 1:250,000 topographic map printed on a transparent mylar base could be overlain on the image to provide the simultaneous topographic information necessary to satisfactorily interpret LANDSAT tonal and textual patterns in terms of avalanche hazards.

The highest level of avalanche hazard is known or active avalanche hazard zones compiled from existing detailed maps (1:31,680 or larger). Although the avalanches in this zone are not necessarily the most dangerous, there is a very high probability that more avalanches will occur in the future.

## REGIONAL AVALANCHE HAZARD MAPS

Avalanche hazard maps were prepared for three contiguous 1:250,000 quadrangles in central Colorado (Plates 1, 2, and 3): Leadville on the north, Montrose, and Durango, on the south (Fig. 5 ). The maps cover the bulk of the avalanche terrain in Colorado, and include nearly all of the areas for which detailed avalanche hazard maps have been prepared. It was originally intended to compile the avalanche hazard mapping on to a single 1:500,000 topographic base map, but significant detail would be lost, so the 1:250,000-scale format was adopted.

Unlike most kinds of maps, hazard maps may produce rapid and far-reaching social and economic impact in the areas they cover. Furthermore, there is no guarantee that the maps will be understood and correctly used. Indeed, it is possible that they will be improperly used, either intentionally or accidentally, to further a particular special interest, perhaps with disastrous results. Hazard mappers must constantly strive for impartiality and consistency in their mapping, so that all equivalent hazards are treated the same. The maps must also be accurate and reliable, if they are to serve a useful function.

The snow avalanche hazard maps prepared for this investigation are largely experimental, both in hazard classification scheme and technique of preparation. Results of the evaluation of the mapping indicate a level of accuracy above what was originally anticipated. Yet, these maps are not equivalent to detailed maps prepared from large-scale air photo analysis and field studies, and we have attempted to clearly and completely describe the limitations, as well as the capabilities, of regional avalanche hazard mapping based on LANDSAT imagery analysis. Neither INSTAAR nor NASA can assume any liability for mapping errors or misuse of these experimental maps.



APPLICATION OF LANDSAT DATA TO THE IDENTIFICATION AND  
DELIMITATION OF LANDSLIDES

INTRODUCTION

LANDSAT imagery has several properties that may make it useful for the mapping of landslides:

i). the small scale of the imagery may aid the delimitation of large landslides, which may be obscured by the detail of large-scale underflight photography

ii.) individual bands may contain different information applicable to landslide recognition

iii) because LANDSAT coverage is repetative, seasonal variation in surface conditions may be used for interpretation

iv) LANDSAT data are amenable to computer processing.

The objectives of this research were:

1) to determine whether landslides can be identified and delimited on LANDSAT imagery, and which methods of investigation are the most appropriate,

2) to determine the accuracy with which landslides can be identified, and how this accuracy is influenced by terrain conditions, and

3) to decide whether LANDSAT can be used to map landslides on a regional scale - for instance on a state-wide basis.

For the purpose of this study, a landslide is defined as having some or all of the characteristics illustrated in Fig. 6. These are features mainly of rotational landslides; translational landslides and debris flows display other characteristics. However, the identification of the characteristics shown in Fig. 6 is a simple test of landslide recognition on

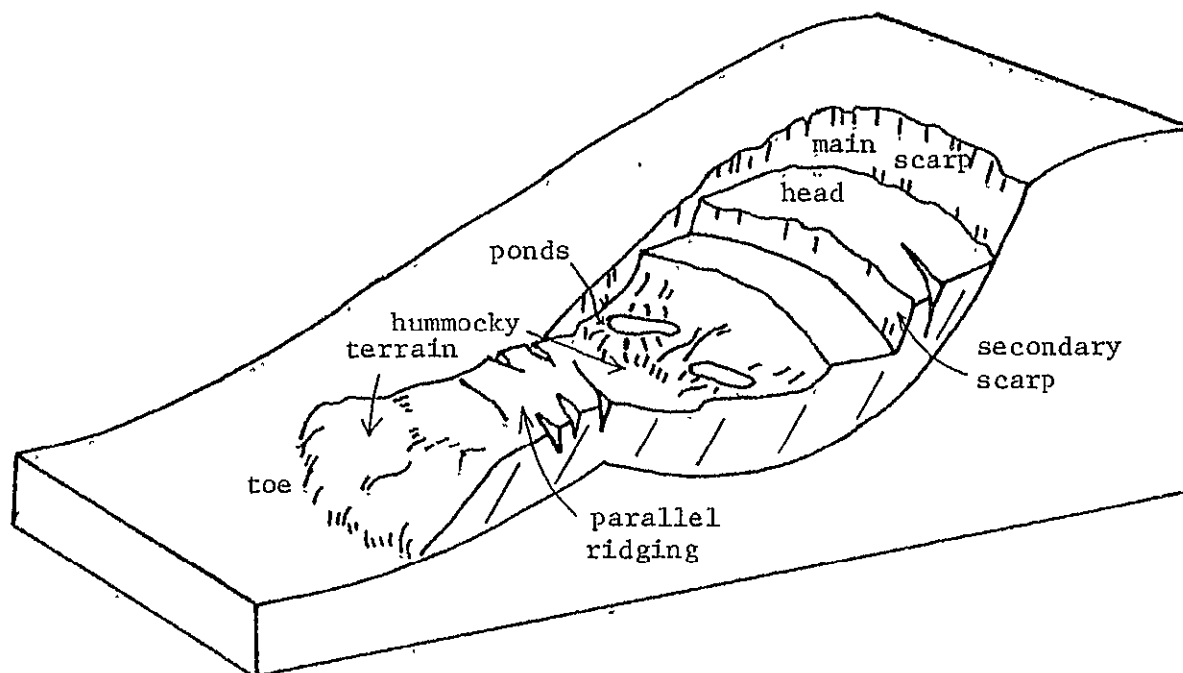


Figure 6. A block diagram of the characteristics of a rotational landslide (13).

LANDSAT imagery.

Two procedures were followed during the study:

- 1) identification of features from known landslide areas recognizable on LANDSAT imagery, and
- 2) the mapping of landslides from LANDSAT imagery onto 1:250,000 topographic maps in unknown areas, and without reference to any source except LANDSAT. Some of these areas were later checked against field work and existing maps.

The most appropriate methods of utilizing LANDSAT imagery for landslide identification were sought throughout the study.

Two major methods of investigation were used:

- 1) nine by nine inch transparencies were examined under a Bausch and Lomb Zoom 240 Stereoscope mounted on a Mims-3 light table, and
- 2) 1:250,000-scale prints produced from LANDSAT 70 millimeter negative transparencies were analyzed.

Generally, the stereoscopic analysis was most useful for detailed landslide identification, while the prints were suitable for regional analysis.

A maximum optimum magnification of 10 to 15 times was possible using the stereoscope. Prints could be enlarged to a maximum scale of about 1:250,000, after which scan-lines became distracting. Prints of about this scale were reasonably useful, because of their compatibility with landslide and geologic maps prepared at the same scale. Paired frames were viewed in pseudostereo using 2 bands of the same scene as a stereopair, and individual frames in mono.

#### IDENTIFICATION OF LANDSLIDE FEATURES

Various types of terrain in southern and western Colorado were investigated (Fig. 7). These include areas of high relief (central San Juan Mountains) in

the Durango 2 degree quadrangle, areas of predominantly fluvial dissection (the Roan Cliffs region) in the Grand Junction 2 degree quadrangle; the Sawatch Range and plateaus (the Grand Mesa region) in the Montrose 2 degree quadrangle; and the eastern portion of the Cortez 2 degree quadrangle. The investigation included different scales of landsliding ranging from relatively large areas, for example the Grand Mesa and Cerro Summit areas (Figs. 8 and 9), each over 30 square miles, to intermediate slides, such as the Silver Mountain Landslide (Figs. 10 and 11), about 12 square miles, and smaller slides of less than 1 square mile (Fig. 13).

Figure 6 shows a classic, fresh landslide form. Some or all of the features illustrated may be apparent in the field, depending on landslide development and the extent of terrain alteration. In known landslide areas some of these features could be identified on LANDSAT imagery. In many cases one or only a few of the features were recognizable. Several types of patterns on the imagery were useful in identifying and delineating landslides:

- a) tonal mottling
- b) tonal banding
- c) major scarps
- d) secondary scarps
- e) ponds
- f) spatial relation of the features
- g) regional differentiation between landslides and the surrounding terrain.

In order of increasing utility, the principal patterns are: mottling, a major scarp, regional differentiation and ponds.

#### TONAL MOTTILING

Figures 8 and 11 illustrate tonal mottling, defined as a high degree of

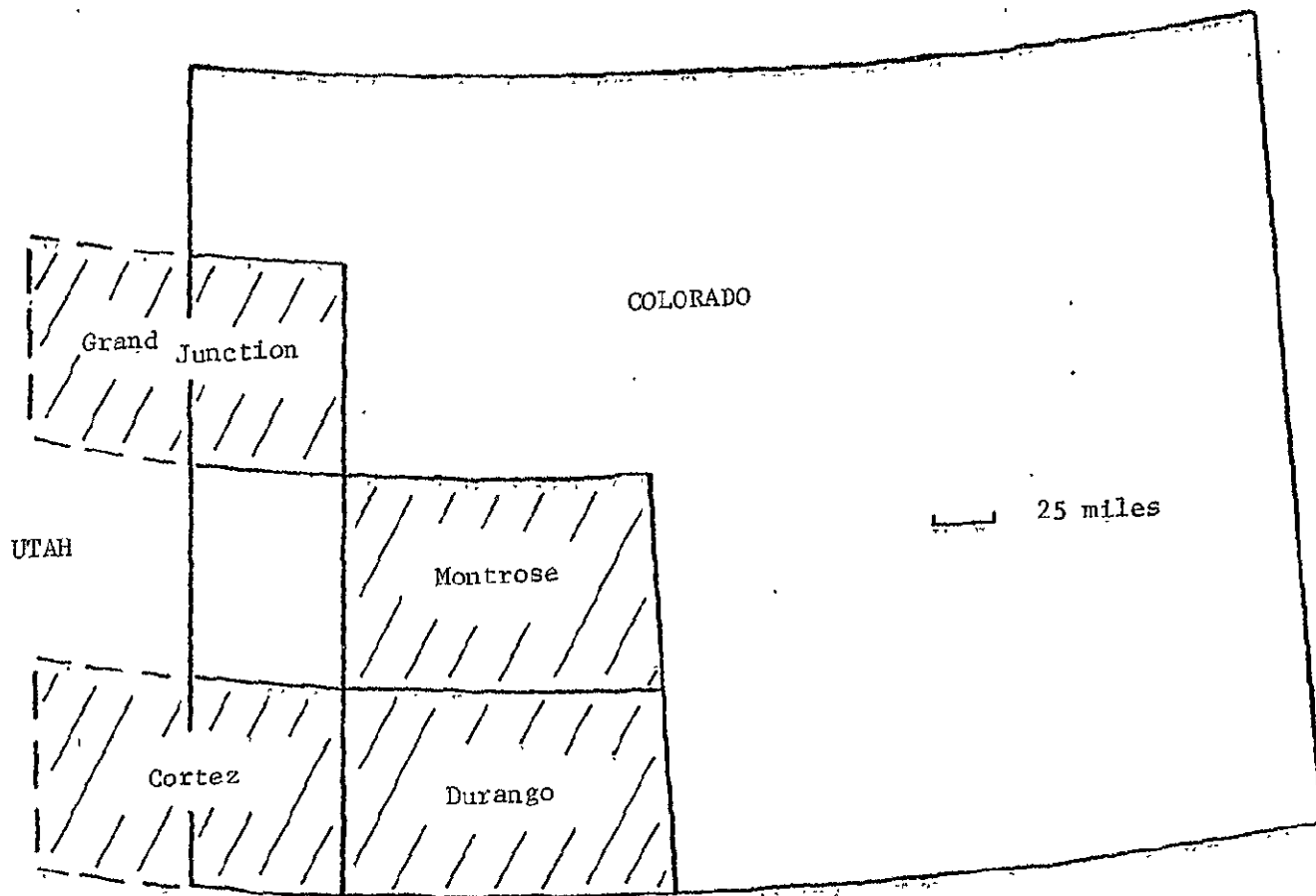


Figure 7. A map indicating the location of the quadrangles utilized in the study.

localized tonal variations. Mottling is thought to be a function of hummocky terrain caused by disruption from landsliding of the previous surface and its drainage network. Therefore, mottling is a function of variation in radiance due to aspect differences. Variations in vegetation type and cover may also affect tonal variation. In some landslides, small areas may represent rotated blocks (Fig. 10).

The area of mottling is thought to represent the area of the slipped mass and, therefore, at best, should give a minimum delimitation of the landslide. However, other areas may have a similar textural appearance on LANDSAT imagery, for example areas covered by glacial drift (Fig. 11).

The mottling characteristic was generally found to be most useful for interpreting larger landslides, although there are major exceptions to this rule, for reasons to be discussed in the succeeding section. In smaller landslides, tonal differences were less easily identifiable due to the low resolution of the LANDSAT system.

Distinctive mottling characterized less than half the landslides present in the study area. A high degree of subjectivity is involved in differentiating mottling due to landsliding from extreme tonal variation caused by local complexities of other surface features.

#### TONAL BANDING

Associated with the mottling characteristic, tonal banding was observed locally in some landslides (Figs. 8 and 11). The banding was interpreted as parallel ridging, which also effects radiance as a function of aspect. Tonal banding was generally used as supplementary evidence because confident interpretation could not be made on its presence alone. Where identified, tonal banding indicates the probable direction of landslide movement perpendicular to the bands.



## MAJOR SCARPS

Due to the strong differences in radiance caused by aspect (shadows), scarp identification was especially useful for landslide recognition. Scarps were identified by dark arcuate features. In many landslides, particularly the smaller ones, such features were the only recognizable characteristics. This, however, presented a major problem as landslide scarps could be confused with other steep slopes or free faces, or even cirque headwalls in mountain regions. Spatial relations between the scarps and the local drainage patterns were helpful in recognizing landslides (Fig. 13). In only a small fraction of landslides could major scarps be identified with confidence. This may be due either to their absence, or lack of expression on the LANDSAT imagery.

## SECONDARY SCARPS

Secondary scarps are expressed on LANDSAT imagery as dark arcuate patterns located downslope of the main scarp. They are smaller than, and sub-parallel to the main scarp. Where a number of secondary scarps occur in a small area, they may form an imagery pattern similar to parallel ridging.

Secondary scarps were identified in only the larger landslide areas (Fig. 8), and were used solely as additional evidence of landslide activity.

## PONDS

Ponds in the hummocky terrain of a slipped mass are evident in landslides of different sizes (Figs. 8 and 11). They are particularly obvious on band 7 images. Ponds are not restricted to landslide terrain and could be identified in less than a quarter of known landslide areas studied.

## SPATIAL RELATIONSHIPS BETWEEN FEATURES

The spatial relationship between features were particularly useful in delimiting the larger landslides. Confidence of identification was greatly

improved in accordance with the number of features that could be observed in any one particular landslide.

#### REGIONAL DIFFERENTIATION BETWEEN LANDSLIDES AND SURROUNDING TERRAIN

On a regional scale, changes in the appearance of otherwise uniform terrain may indicate landslide activity. There is no set rule for general differentiation, but marked textural differences and obvious changes in drainage patterns are good indications of landslide terrain (Fig. 12 and 13).

#### BANDS AND SEASONS OF IMAGERY

Band 7 is the most useful band for landslide recognition because ponds and topographic features are accentuated. For a comparison of bands 5 and 7, see Fig. 10 and 11. Scarps stand out better in band 7 due to shadow enhancement and possibly vegetational differences. Bands 6 and 5 are the next most useful bands, although an examination of bands 7 and 5 together provide most of the available information.

Late-summer imagery (August to October) provided the most cloud-free coverage. Early-snow-season imagery is potentially useful for enhancing slight topographic variation from differential snow cover. However, the greater part of the information could be obtained from snow-free imagery.

#### CHECKING INTERPRETATION

Where interpretation was carried out in unknown areas, regional landslide and geologic maps prepared by Colton et al. (13, 14, 15, and 16), Steven et al. (17) and Tweto et al. (18) were used to check results. Field-checking of landslides in one such area was also carried out in summer 1977 during field work on NASA Grant 06-003-200.

Figure 12 shows a region where landslides were interpreted before field-checking. These areas were later confirmed as landslides, but numerous

other smaller slides in the region were not recognized.

Limitations of LANDSAT imagery for use in identifying landslides stem from the lack of unique spectral characteristics and the scale of the imagery.. The relationship between slope instability and vegetation is insufficiently consistent to warrant the use of tree species as an indicator of landslides. Known landslides are obscured by heavy coniferous forest. However, upper and lower treelines roughly corresponded to the limits of a hillslope region in which landslides are most common.

Landslides occur within a wide range of surficial materials. Therefore, the spectral properties of these materials is not particularly useful in identifying landslide areas.

Since image tones vary according to slope aspect, the imagery expression of a landslide is a function of its position in relation to the sun and the LANDSAT satellite. For example, in Fig. 11 the Silver Mountain and Ames Landslides border a common valley and face west and east, respectively. During the satellite pass, the sun illuminated from the east. The topography of the Silver Mountain Landslide is enhanced by shadow, and readily observable. The Ames Landslide is completely illuminated and appears as an almost consistently bright slope. (Conversely, a landslide can be entirely in shadow, and therefore unidentifiable.) The Ames Landslide is considerably smaller than the slide on Silver Mountain. However, other small landslides are evident where illumination conditions are more favorable.

The morphology of a landslide is its most distinctive and easily recognizable characteristic. Unfortunately, topography is difficult to interpret on LANDSAT imagery due to the small scale. Pseudostereo viewing of two essentially identical LANDSAT frames does not substantially accentuate topography..

However, enlargements of imagery, particularly in conjunction with pseudo-stereo interpretation, reveal some landslide morphology. The effectiveness of this technique is limited by the decrease in image quality that accompanies the enlargement of imagery.

Even though the larger landslides are generally easier to identify than small ones, detectability of the small slides varies greatly according to aspect, vegetation masking, the degree of topographic expression, development of the landslide, and the certainty with which topographic features could be identified. The influence of aspect is most prevalent in areas of high relief. The association between scale, relief and aspect, and its effect upon landslide identification became apparent during the mapping of the Sawatch Mountains and the eastern portion of the Cortez 2 degree quadrangle (Figs. 13 and 14). In neither case are large areas of hummocky landslide terrain evident, but smaller landslides of similar size occur in these contrasting terrains. However, the Sawatch Mountains are much more difficult to interpret and map because of the greater relief. Landslide scarps are easily confused with alpine free faces, since extreme aspect effects reduce the observation of downslope features (Fig.14). Several arcuate scarps in Mesa Verde National Park (Cortez sheet) exist in sharp contrast to the linearity of adjacent valleys (Fig. 13). More even illumination of the shallow valleys in the Cortez area facilitates the observation of a greater number of landslide characteristics, and thus increases identification capability. This example also demonstrates the importance of observing as many features as possible and utilizing the interpretation of associations between them. Otherwise, hummocky terrain, by itself, could just as well be glacial drift, and a small grouping of ponds could simply reflect interception

of the water table.

In general, the ability to identify landslides on LANDSAT imagery is limited by the fact that LANDSAT information is predominantly spectral, and landslides do not have characteristic spectral properties. The spectral appearance of a particular slide depends mostly on the nature of the surface and its orientation rather than the landslide itself. The imagery expression of morphology, the most consistent characteristic of landslides, is variable on LANDSAT imagery. From experience, underflight photography reveals significantly greater and more consistent information on landslide location and character.

Also, accurate mapping of landslides is hindered by the inability to determine distinct boundaries. The upper limit of a landslide is generally marked by a main scarp, but the lower boundary is often vague. For example, the toe of a landslide may extend well below the limit evident on the LANDSAT imagery (Fig. 8).

The recognition of landslide features varies according to conditions of terrain. Some of the larger landslide areas, such as those on the Grand Mesa and Silver Mountain (Figs. 8 and 11), display recognizable features. In contrast, the Cerro Summit-Cimmaron Ridge region, despite its large size, displays few landslide characteristics on LANDSAT imagery (Fig. 9). In all bands, this landslide area appears relatively uniformly grey, while localized white areas in the northern part of the region are due to the presence of gravel-topped plateaus. This information alone is insufficient to diagnose landsliding. There are a number of possible reasons for the lack of imagery evidence of landsliding:

- 1) in the southern part of the landslide area, coniferous vegetation

may obscure landslide features,

2) much of the recent landslide activity, particularly in the northern portion of the region, is occurring in several small areas which may be too small to see on LANDSAT imagery, and

3) in the northern portion of the area, relief is insufficient to accentuate topographic slope features.

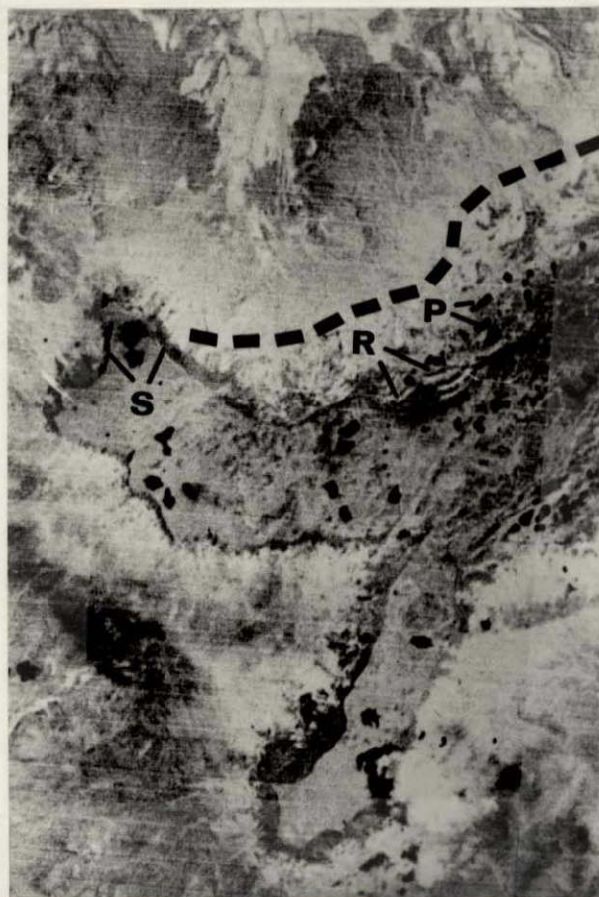
It would seem, therefore, that there is an optimum amount of relief necessary for landslide identification, depending on site conditions. Whereas much relief obscures landslide information because of slope aspect effects, too little relief also appears to be undesirable.

#### CONCLUSIONS

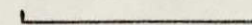
Some landslides in Colorado can be identified and, to a degree, delimited on LANDSAT imagery, but the conditions of their identification are highly variable. Because of local topographic, geologic, structural and vegetational variations, there is no unique landslide spectral appearance on LANDSAT imagery. Accordingly, in most cases, supplementary information is necessary in order to positively identify landslide areas.

Since morphometric features are not consistently recognizable, the mapping of landslides is subject to much variation in accuracy. Consequently, LANDSAT imagery is not recommended as a regional mapping tool in areas similar to Colorado. However, as has been described, some areas do demonstrate convincing evidence of landsliding. Therefore, it is possible that in other less well-known regions where the scale of activity is particularly large, where geologic conditions are more uniform, and where a strong case may be made for frequent monitoring of landslide activity, LANDSAT imagery may have greater application. Also, LANDSAT imagery may be a suitable tool for landslide mapping in areas where there is no alternative (larger scale) imagery.

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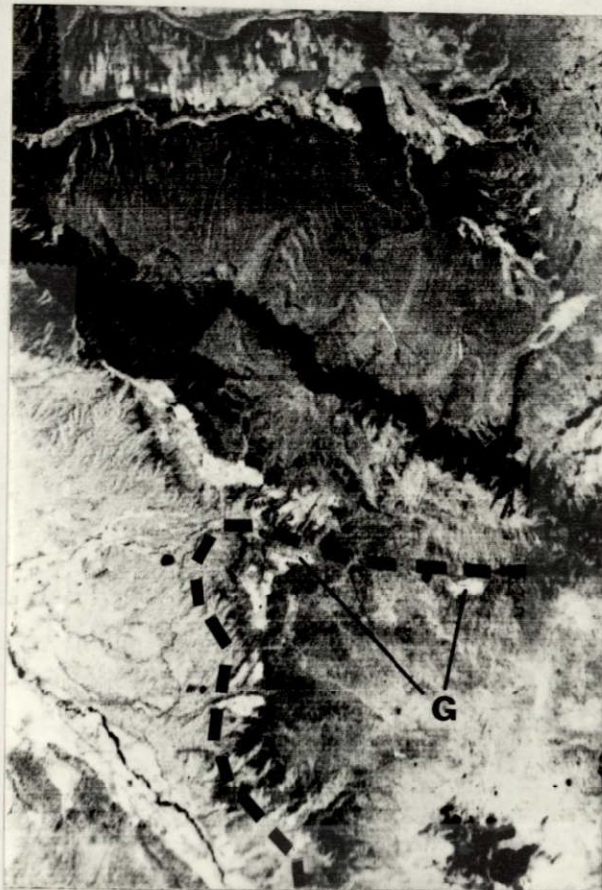
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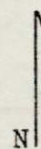
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Figure 8. Part of LANDSAT frame 2170-17141 showing Grand Mesa Landslide (Grand Junction quadrangle)  
S - major scarps; R - parallel ridging; P - ponds; dotted line represents northern  
extent of landslide interpreted from LANDSAT (band 7).





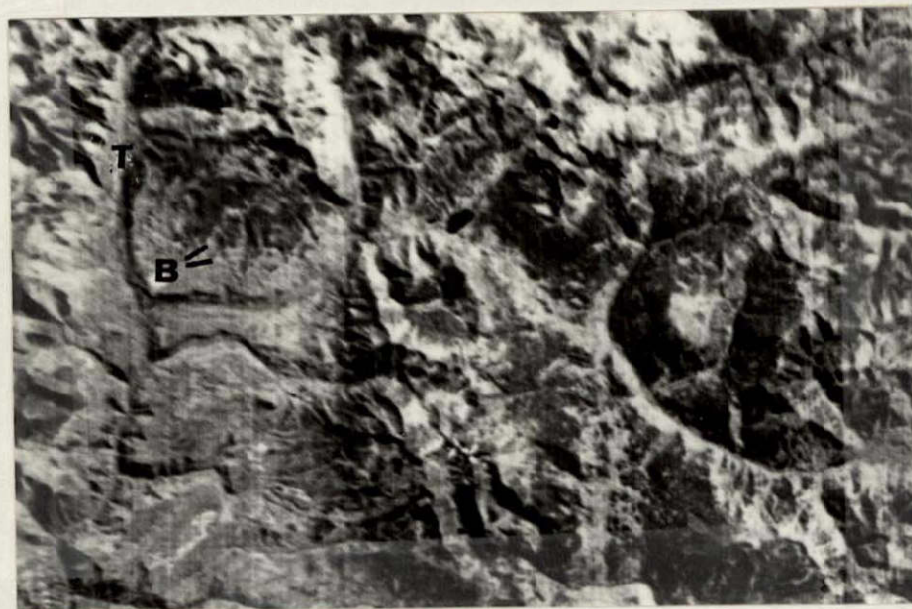
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Figure 9. Part of LANDSAT frame 2187-17080 showing Cerro Summit Landslide Region (Montrose quadrangle). G - gravel terraces; dotted line represents western and northern boundaries of landslide (band 7).

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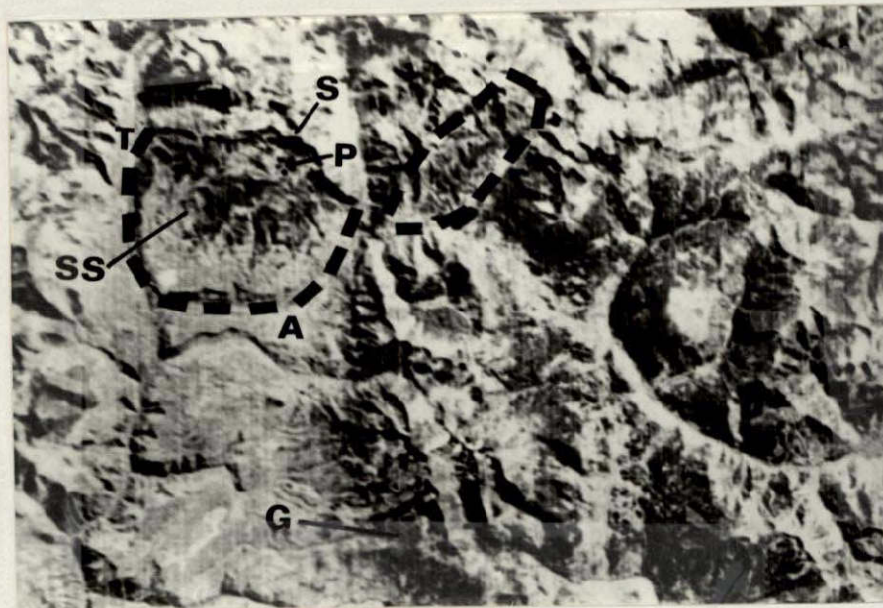
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Figure 10. Part of LANDSAT frame 1066-17254 showing Silver Mountain Landslide, San Juan Mountains (Durango quadrangle). T - location of town of Telluride; B - rotated landslide blocks; (band 5).



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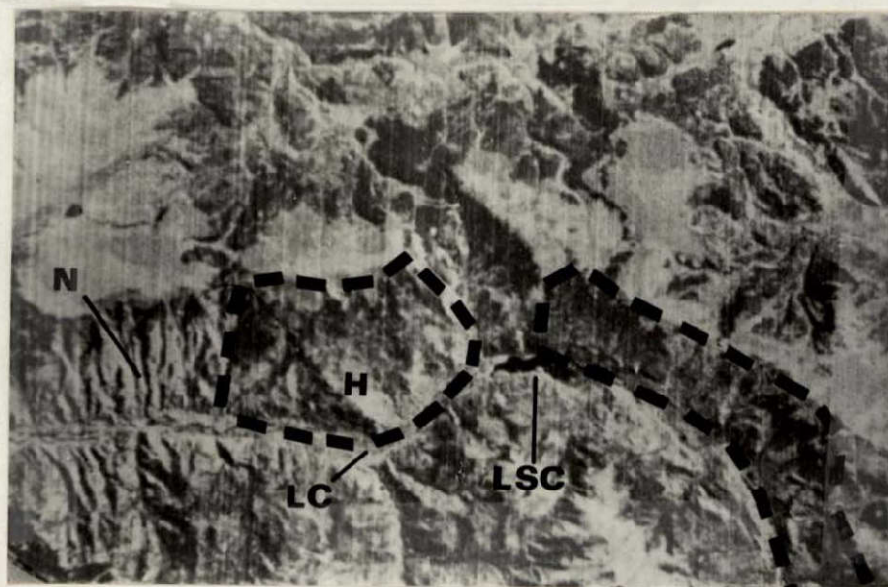
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Figure 11. Part of LANDSAT frame 1066-17254 showing Silver Mountain Landslide. S - major scarp of the slide; SS - secondary scarps; P - ponds; R - parallel ridging; T - location of town of Telluride; G - glacial drift; A - location of Ames Landslide; dotted line delimits both the Silver Mountain and Yellow Mountain Landslides (band 7).



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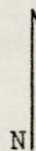
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Figure 12. Part of LANDSAT frame 1425-17190 showing landslides in the area of Lake City, San Juan Mountains (Durango quadrangle). H - hummocky terrain; N - 'normal' drainage pattern; L - location of Lake City; LSC - location of Lake San Cristobal; dotted line represents boundaries of landslides recognized on LANDSAT (band 5).



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Figure 13. Part of LANDSAT frame 2098-17143 showing two small landslides mapped from LANDSAT (L). The flatness of the terrain prohibits the interpretation from LANDSAT of many known landslides in this area (band 7).





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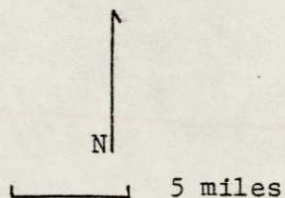


Figure 14. Part of LANDSAT frame 2187-17080 showing the Sawatch Mountain Range in the area of Taylor Park Reservoir (Montrose quadrangle). Intermittent cloud cover and shadow effects in mountain regions can make interpretation from LANDSAT difficult (band 7)





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Figure 15. Part of LANDSAT frame 2170-17141 showing the Roan Cliffs area, north-west of Grand Junction (Grand Junction quadrangle). This region provides a good example of an area possessing many landslides unidentifiable on LANDSAT due to the extreme effect of topography (band 5).



## REFERENCES

- (1) R. L. Armstrong, E.R. LaChapelle, M.J. Bovis, and J.D. Ives. Development of methodology for evaluation and prediction of avalanche hazard in the San Juan Mountain area of southwestern Colorado. INSTAAR Occ. Paper 13, Boulder, Colorado, 1974. 141pp.
- (2) A.I. Mears. Guidline and methods for detailed snow avalanche hazard investigations in Colorado. Colo. Geol. Survey Bull. 38, Denver, 1976. 125pp.
- (3) H. Frutiger and M. Martinelli. A manual for planning structural control of avalanches. U.S. Forest Service Research Paper RM-19, 1966.
- (4) M. Martinelli. Avalanche sites, their identification and evaluation. U.S. Forest Service Agriculture In. Bull. 360, 1974. 26pp.
- (5) A.F. Fukui. The classification of avalanches in Japan. Int. Symp. on Sci. aspects of Sci. Hyde, No. 69, 1966. p. 377-381.
- (6) R.I. Perla. Advances in North American avalanches technology. U.S.D.A. Forest Service Gen. Tech. Rept. RM-54.
- (7) M. de Quervain, et al. Proposal of the working group on avalanche classification of the international Commission on snow and ice. Hydrol. Sci. Bull. 18, 1973. 391-402pp.
- (8) Hans Frutiger. Snow avalanche along Colorado mountain highways. U.S. Forest Service Res. Paper RM-7, 1964. 85pp.
- (9) M.J. Bovis. Natural hazards of San Juan County Colorado--Report to the San Juan County Planning Commission. INSTAAR, University of Colorado, Boulder, 1976.

- (10) M.J. Bovis. Natural hazards of San Miguel County, Colorado--Report to the San Miguel County Planning Commission. INSTAAR, University of Colorado, Boulder, 1976.
- (11) M.J. Bovis. Natural hazards of Ouray County, Colorado--Report to the Ouray County Planning Commission. INSTAAR, University of Colorado, Boulder, 1976.
- (12) D.H. Knepper. Natural hazards of northern Hinsdale County, Colorado--Report to the Hinsdale County Planning Commission. INSTAAR, University of Colorado, Boulder, 1977.
- (13) R.M. Batson, Kathleen Edwards and E.M. Eliason. Computer-generated shaded relief images. U.S. Geol. Survey Jour. Research, V. 3 No. 4, 1975. 401-408.
- (14) D.J. Varnes. Landslide types and processes. p. 20-47 in Eckel, E.B. (ed.) Landslides and Engineering Practice. NAS-NRC Publication 544, 1958.
- (15) R.B. Colton, J.A. Holligan, L.W. Anderson, and J.W. Whitney. Preliminary map of landslide deposits, Grand Junction Quadrangle, Colorado and Utah, U.S. Geol. Surv. Misc. Field Studies Map MF-697, 1975a.
- (16) R.B. Colton, L.W. Anderson, J.A. Holligan, P.E. Patterson, and K.C. Shaver. Preliminary map of landslide deposits, Cortez Quadrangle, Colorado and Utah. U.S. Geol. Surv. Misc. Field Studies Map MF-699, 1975b.

- (17) R.B. Colton, P.E. Patterson, J.A. Holligan, and L.W. Anderson.  
Preliminary map of landslide deposits, Montrose Quadrangle,  
Colorado. U.S. Geol. Surv. Misc. Field Studies Map MF-702,  
1975c.
- (18) R.B. Colton, J.A. Holligan, and L.W. Anderson. Preliminary map of  
landslide deposits, Durango Quadrangle, Colorado. U.S. Geol.  
Surv. Misc. Field Studies Map MF-703, 1975d.
- (19) T.A. Steven, P.W. Lipman, W.J. Hail, F.Barker, and R.G. Luedke.  
Geologic map of the Durango Quadrangle, southwestern Colorado.  
U.S. Geol. Surv. Misc. Geol. Inv. Map I-764, 1974..
- (20) O. Tweto, T.A. Steven, W.J. Hail, and R.H. Moench. Preliminary  
geologic map of the Montrose Quadrangle, southwestern  
Colorado. U.S. Geol. Surv. Misc. Field Studies Map MF-761,  
1976.

## SOURCES OF DETAILED AVALANCHE MAPPING

- I. Hans Frutiger. Snow avalanches along Colorado mountain highways. U.S. Forest Service Res. Paper RM-7, 1964 (1:24,000).
- II. Bruce Bryant. Map showing avalanche areas in the Aspen quadrangle, Pitkin County, Colorado. U.S. Geological Survey Map I-785-G, 1972 (1:24,000).
- III. Colorado State University. Snow avalanche areas, Upper Roaring Fork and the high valleys, Pitkin County, Colorado. Colorado State University Environmental Analysis, 1974 (1:31,680).
- IV. Colorado State University. Snow avalanche areas, Lower Roaring Fork Valley, Pitkin County, Colorado. Colorado State University Environmental Analysis, 1974 (1:31,680).
- V. Colorado State University. Snow avalanche areas, Crystal River Valley, Pitkin County, Colorado. Colorado State University Environmental Analysis, 1974 (1:31,680).
- VI. Colorado State University. Snow avalanche areas, Fryingpan River Valley, Pitkin County, Colorado, 1974 (1:31,680).
- VII. Eagle County Planning Department. Snow avalanche hazard maps--Sheets 1D, 2D, 3D, and 5D. Charles S. Robinson and Associates, Inc., Golden, Colorado, 1975 (1:24,000).
- VIII. M.J. Bovis. Natural hazards of San Juan County, Colorado-- Report to the San Juan County Planning Commission. INSTAAR, University of Colorado, Boulder, 1976 (1:24,000).
- IX. M.J. Bovis. Natural hazards of San Miguel County, Colorado--Report to the San Miguel County Planning Commission. INSTAAR, University of Colorado, Boulder, 1976 (1:24,000).
- X. M.J. Bovis. Natural Hazards of Ouray County, Colorado--Report to the Ouray County Planning Commission. INSTAAR, University of Colorado, Boulder, 1976 (1:24,000).
- XI. D.H. Knepper. Natural hazards of northern Hinsdale County, Colorado-- Report to the Hinsdale County Planning Commission. INSTAAR, University of Colorado, Boulder, 1977 (1:24,000).